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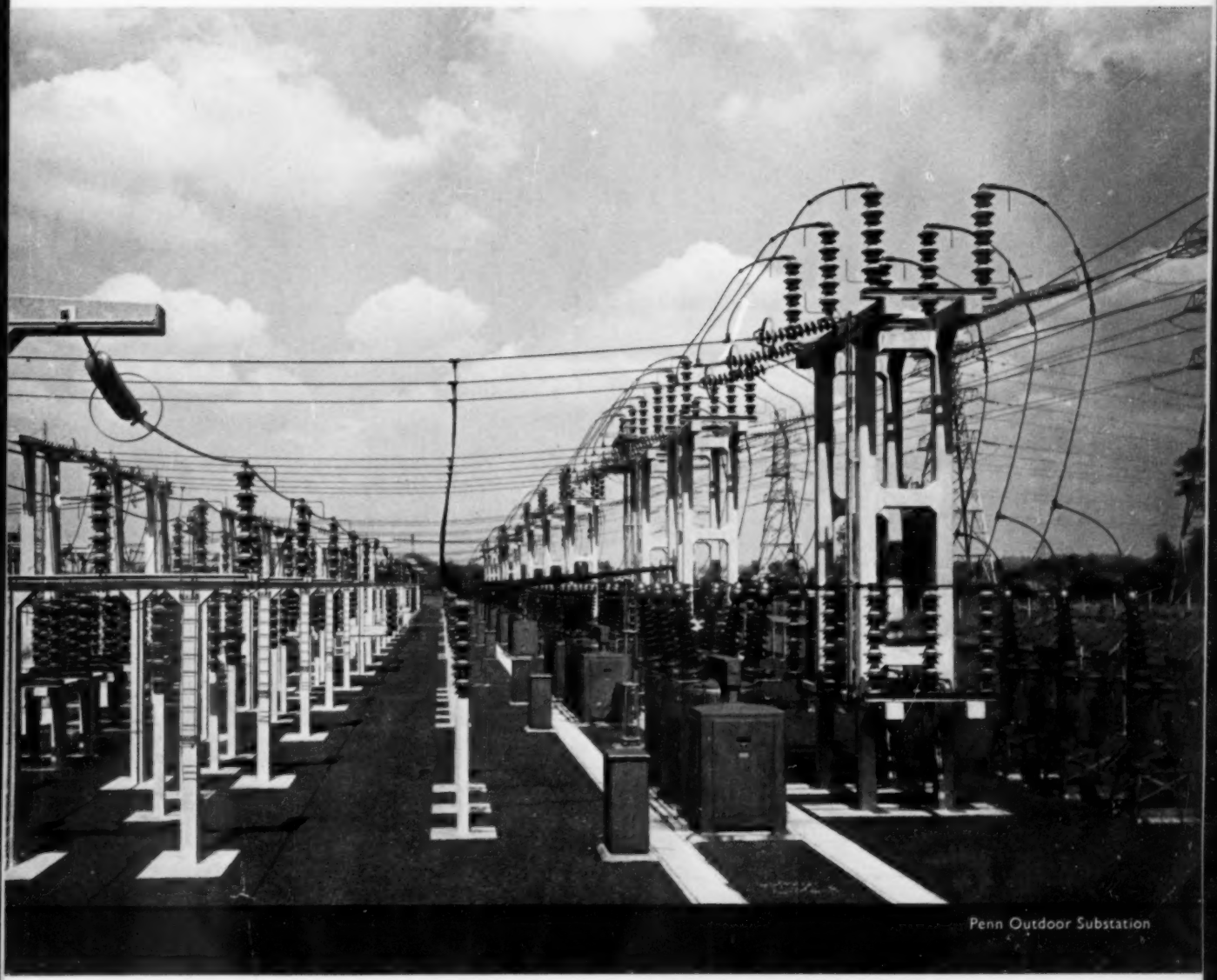

Penn Outdoor Substation

THE GENERAL ELECTRIC COMPANY LIMITED OF ENGLAND

Volume 28, number 3

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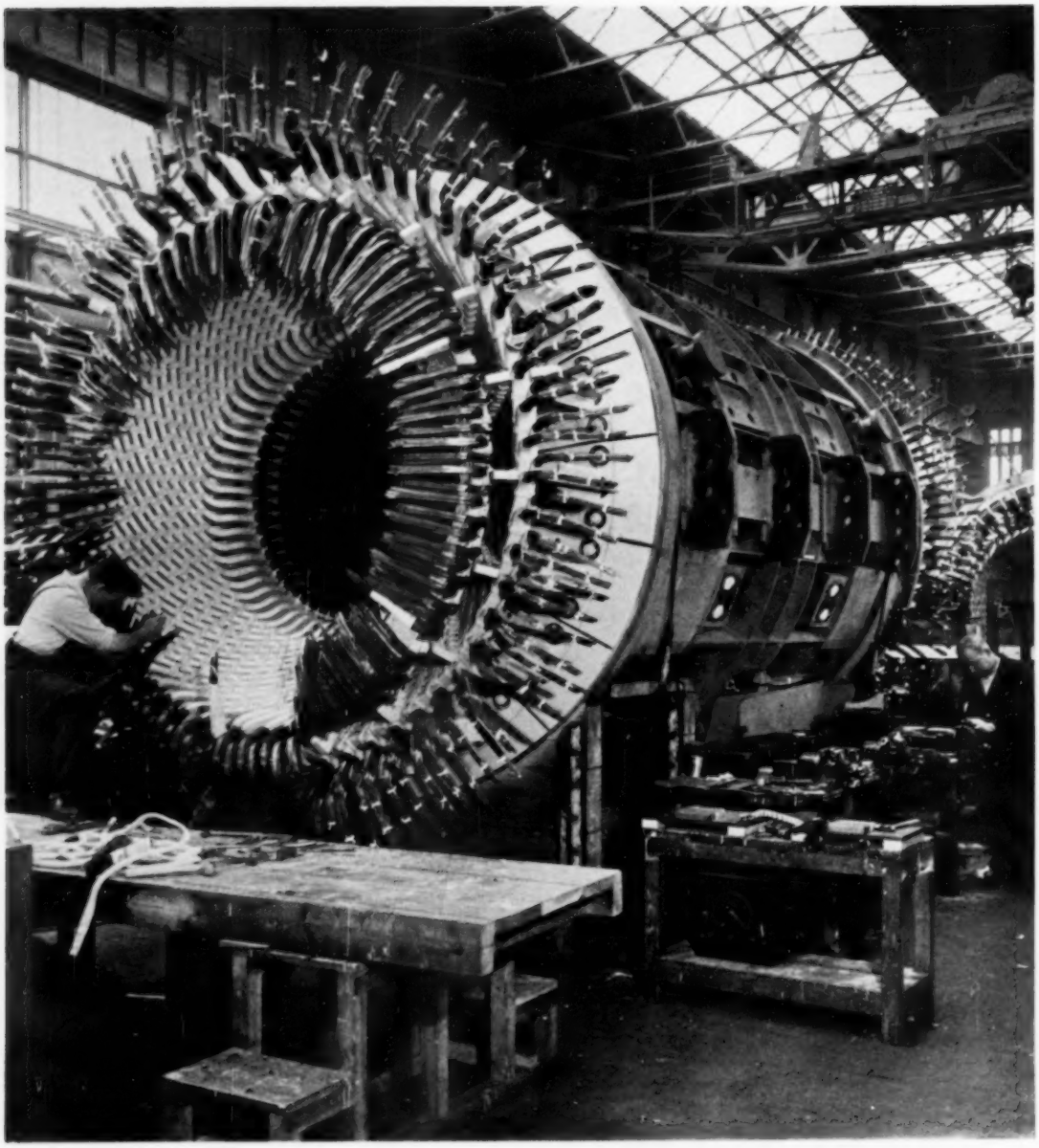
COVER PICTURE

The C.E.G.B. 132 KV switching station at Penn, near Wolverhampton. The whole of the electrical equipment for this station, including 17 oil circuit-breakers rated at 3500 MVA, was supplied by G.E.C.



Winding the inner stator casing of a 200 MW turbo-alternator for the Kincardine Generating Station of the South of Scotland Electricity Board

International Systems Control Ltd.

A New British Company for Advanced Automation.

THE General Electric Company Limited of England has recently joined with Thompson Ramo Wooldridge Inc. of Los Angeles, California, in forming a new British company to market industrial process control systems using digital computers. The new Company—International Systems Control Limited—starts with a capital of £430 000 equally shared by the parent companies. Its territory is the United Kingdom, the Commonwealth Countries and the European Free Trade Area.

Mr. O. W. Humphreys (Technical Director of the G.E.C.) is the Chairman of the new company and Dr. D. N. Truscott (General Manager of Electronics Division, G.E.C.) is Managing Director. Dr. E. M. Grabbe, T.R.W.'s Senior Staff Consultant on Automation is Deputy Managing Director and the other Directors are Mr. G. W. Fenimore (Vice-president, T.R.W. International Inc.), Mr. W. A. C. Maskell (Managing Director, Telecommunications Group, G.E.C.) and Mr. M. E. Mohr (Vice-president, Electronic Systems and Equipment Group, T.R.W.).

As early as 1955 T.R.W. recognized that complex industrial processes could operate more profitably if controlled by computer, and since then they have applied the technique to a diverse range of industries including cement works, oil refineries, chemical manufacture, electricity generating stations and complex test installations for guided missiles.

In such processes the many parameters controlling the product and its manufacture are constantly monitored and signals sent directly to the computer, which compares them with the value required for optimum operation of the plant. When any deviation occurs, the computer calculates the effects on inter-related measurements and automatically sends out signals which actuate plant controls and make appropriate corrections. Since the entire procedure occupies only a matter of seconds the optimum state is maintained far more closely than it could be by manual or semi-automatic systems.

A second type of application for which the standard RW 300 industrial computer is ideally suited is the recording of process data. In addition to recording plant instrument-reading at frequent intervals, the computer can carry out on them the calculations necessary to produce results in the form required for subsequent use. These are then recorded by printing out or on punched tape. The automatic process-control features of the computer can always be exploited later, if desired.

An extension of this scheme is very attractive in pilot plants or complex testing procedures such as are frequently found in high-temperature or structural testing laboratories, wind-tunnel installations, guided missile test benches and similar situations. Readings from large numbers of dispersed points have to be taken simultaneously and at frequent intervals, with immediate warning if any dangerous conditions are developing as the test proceeds.

The programme for the complete range of tests can be stored in the computer which takes over from the usual test controller and, if necessary, amends its action according to data accumulated from the test. It then carries out its data logging function, making all the otherwise time-consuming calculations needed on the data it has received, and printing out the final results of the test in immediately useful form. The flexibility of the RW 300 computer—the standard control computer which International Systems Control Ltd. will use—is such that substantial variations in its action can be introduced rapidly simply by re-programming.

This RW 300 computer installation automatically controls two processes in the plant of B. F. Goodrich Chemical Co., at Calvert City, Kentucky, U.S.A.

The efficiency of operation was increased, the uniformity of product improved and operating costs were reduced by its introduction.

International Systems Control Ltd. are located at East Lane, Wembley, Middlesex, in a modern building on the G.E.C. Estate. The telephone number is ARNold 1244 and the cable address 'DIGITISE WEMBLEY'.

Modern Developments in the Control and Protection of Synchronous Motors

By R. E. SWAN, A.M.I.E.E., Engineering Group, Witton.*

INTRODUCTION.

IN the application of synchronous motors two of the most critical problems are concerned with ensuring that the minimum of disturbance to the supply system takes place during the starting procedure and that the machine is adequately protected during its operation. Certain aspects of the control and protection of synchronous motors have received inadequate attention in the past and this article deals with these considerations, outlining the apparatus now available for inclusion in the comprehensive scheme.

STARTING METHODS.

A salient-pole synchronous motor may be started by using a pony motor to run it up and then synchronizing it to the supply system, but, although this method gives an ideal starting characteristic without any system disturbances, it may tend to be uneconomic, both in capital cost and losses, since the latter are increased during normal running of the synchronous motor by the windage of the pony motor. Frequently therefore, it is necessary to resort to starting the synchronous motor by other means whereby it is connected to the supply system and allowed to accelerate as an induction motor. The obvious direct-to-line method, using the pole-face windings as a squirrel cage, is not used very frequently owing to the high starting currents, and the most commonly used methods are, therefore, by reactor or auto-transformer starting. In the reactor method the high starting current is limited by the series reactor during starting, the reactor being shorted out towards the end of the starting sequence. The auto-transformer method, on the other hand, is a reduced-voltage starting system wherein the line current is reduced as the square of the auto-transformer tapping.

The other class of motor to be considered is the synchronous induction motor in which the pole-face windings are varied externally during the starting sequence so that the motor starts as a slipring induction machine. The synchronous induction motor starts with its exciter permanently connected in the rotor starting-winding circuit, but the salient-pole synchronous induction motor starts with its field winding initially open-circuited and then connected across a discharge resistor prior to connexion to the exciter.

In all these schemes of starting there are various transient conditions as the circuits are changed by the operation of switchgear and the application of the field. It is with a view to minimizing these surges that consideration has been given to the development of a slip-frequency relay which will respond not only to speed requirements, as in earlier forms, but also to the selection of the most advantageous point on the induced rotor-voltage wave to give the minimum disturbance.

FIELD APPLICATION.

At slip frequency the rotor poles are continuously slipping back with respect to the poles of the rotating field set up in the stator. The maximum flux is created when poles of differing polarity are opposite each other and this, therefore, represents the position of easiest

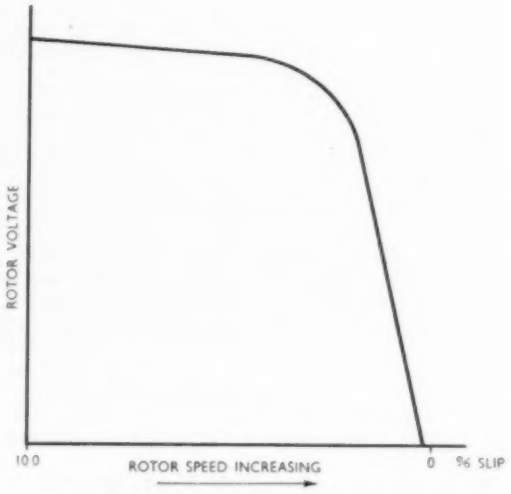


Fig. 1.—Relationship between induced rotor voltage and speed.

*Now at the Projects Group of the Central Electricity Generating Board at Guildford.

synchronizing giving the minimum of system disturbance. A slip-frequency relay should therefore be capable of applying the field not only at the correct speed but also at the correct point on the wave of induced rotor voltage.

Fig. 1 shows the relationship between induced rotor voltage and speed, and this curve may then be reproduced to give the wave shown in fig. 2. With a flux-decay relay (slugged against drop-off at any frequency above the lowest slip frequency and in series with a half-wave rectifier to block out unwanted half-waves) connected across a part of the field discharge resistor, synchronizing may be achieved under the most advantageous conditions. Setting variations may be obtained by a parallel variable resistor, and any possibility of pumping is eliminated by sealing the relay in once it has operated.

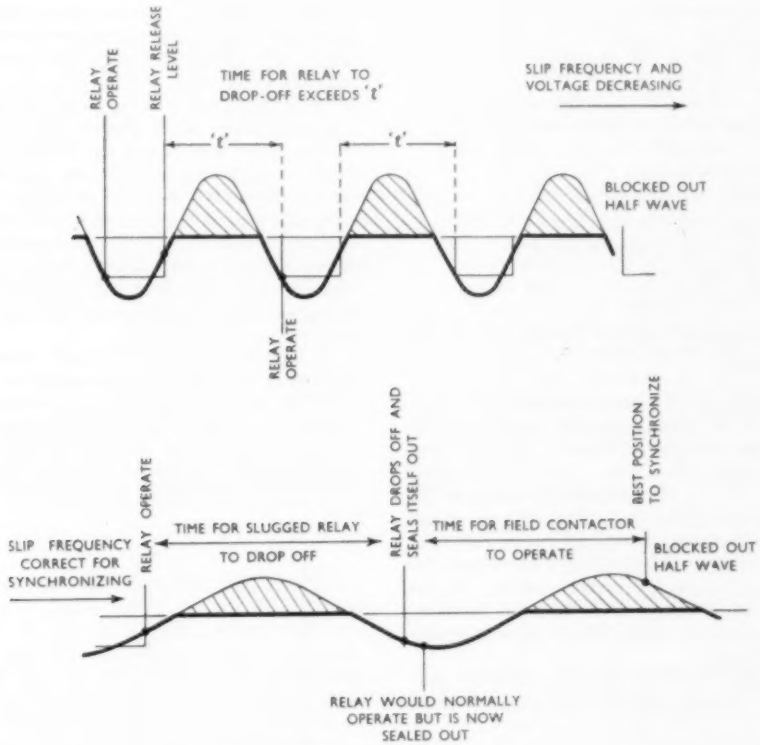

RELAY OPERATE
RELAY RELEASE LEVEL
TIME FOR RELAY TO DROP-OFF EXCEEDS 't'
SLIP FREQUENCY AND VOLTAGE DECREASING
't'
't'
BLOCKED OUT HALF WAVE
RELAY OPERATE
RELAY DROPS OFF AND SEALS ITSELF OUT
BEST POSITION TO SYNCHRONIZE
RELAY OPERATE
TIME FOR SLUGGED RELAY TO DROP OFF
TIME FOR FIELD CONTACTOR TO OPERATE
SLIP FREQUENCY CORRECT FOR SYNCHRONIZING
BLOCKED OUT HALF WAVE
RELAY WOULD NORMALLY OPERATE BUT IS NOW SEALED OUT

Fig. 2.—Operation of slip-frequency relay.

As an alternative device to the flux-decay relay an electronic scheme using transistor units may be considered. In this arrangement the low-frequency rotor voltage is converted into the output of a square-wave generator which is then fed into a six stage NOR unit binary counter. This counter is used for rotor-heating protection in addition to field application, and for field application purposes a signal is obtained after the first stage and fed to a time-delay circuit. This time-delay circuit operates when the motor has reached the appropriate speed, and the application of the field is then determined by a second time-delay feature which ensures the application at the most suitable point on the wave. This second time-delay may be obtained by means of electro-mechanical relays or a further CR circuit, but the introduction of a phase shift into the square-wave generator input circuit is the most simple method.

PROTECTION.

The standard protective requirements for a synchronous motor may be defined fairly readily as:

(*a*) A thermal relay giving overcurrent and phase unbalance protection with high-set instantaneous overcurrent and earth fault features.

(*b*) Undervoltage protection to ensure that the supply is healthy before starting and to give some measure of protection in the event of supply failure during running. Owing to the inertia of the machine and its coupled load, however, any undervoltage relay will be held up for a period of time, and it is frequently neces-

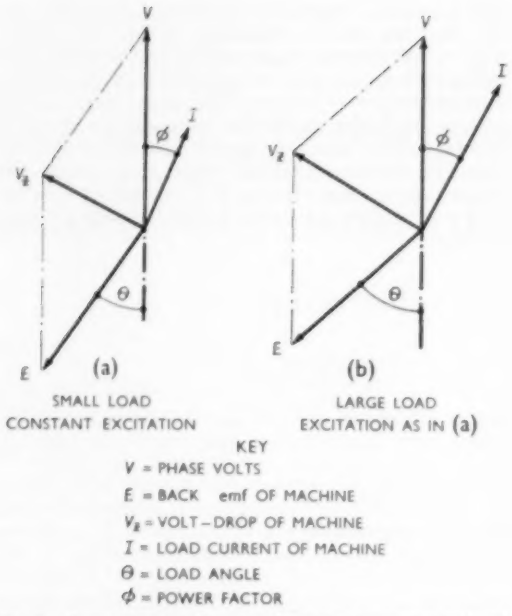


Fig. 3.—Vector diagram of motor subjected to increasing load with constant excitation.

sary, especially in schemes associated with auto-reclosing on the supply feeders, to give special consideration to this problem. Another case requiring special attention is that of a number of motors running on one busbar where, in the event of supply failure, the undervoltage relays of all machines may be held up by the inertia of the largest motor. Past practices have been the use of underpower, reverse power and/or underfrequency relays as a form of back-up protection against supply failure during operation of the motor.

(*c*) Overall differential (circulating current) protection for phase-to-phase and phase-to-earth faults.

(*d*) Field-failure protection.

(*e*) Overpower relay to protect the machine, if a reciprocating drive, against damage due to mechanical overloads or mechanical failure.

Of the protective requirements above, (*b*) supply undervoltage (*d*) field failure and (*e*) excessive mechanical load, will all lead to a loss of synchronism with the supply system which will in turn cause severe mechanical torque variations and considerable heating. In view of these common effects it is possible to use one device to detect a loss of synchronism and this device will in effect operate instantaneously only at impending loss of synchronism. It should, however, be noted that a supply undervoltage relay is an essential item of apparatus since it should be connected to the busbars and give a pre-starting and back-up protection.

It is sometimes found that complete reliance is placed on the thermal overcurrent relay to detect loss of synchronism on the basis of the increase in stator current. This is considered to be bad practice in view of the fact that the stator current increase may be to only, say, 150% full-load current and this may take 2½ to 3 minutes to operate the thermal relay even if the overcurrent elements are set as low as 105%. This approach ignores the fact that during this time very serious mechanical damage may be caused to the machine, and disregards the effects on the power supply system.

LOSS OF SYNCHRONISM.

With a motor operating sychronously the axes of the rotor poles lag behind the stator pole axes by the load-angle. Should the load-angle be increased beyond one half pole pitch the flux linking the rotor and stator poles is insufficient to hold the machine in step and 'pole-slipping' takes place. The load-angle may be increased by increase of mechanical load, inadequate field strength or stator system undervoltage. Fig. 3 shows the vector diagram of motor subjected to increasing load with constant excitation and fig. 4 a typical relationship between load-angle and power-factor. Should pole-slipping occur the stator current will increase, the power-factor become lagging and the motor will be subjected to severe variations of current and torque.

A relay connected to read power-factor could obviously be used to detect extreme load-angles and could be used to trip the motor, or alternatively, if the motor is capable of re-synchronizing against the load, merely tripping the field switch and initiating a re-synchronizing process. For motors which are normally operated at a constant loading a reactive—VA relay

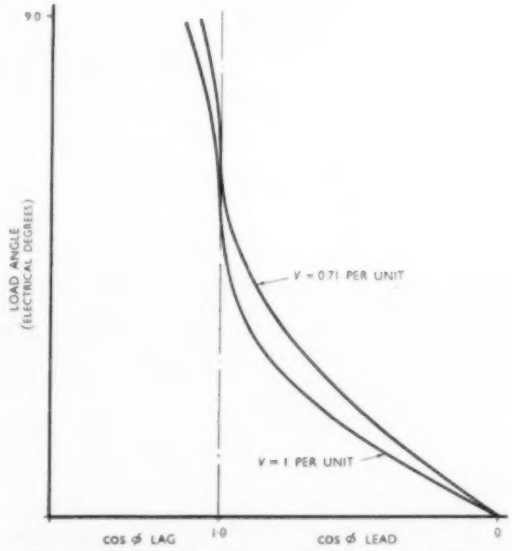


Fig. 4.—Relationship between load angle and power factor.

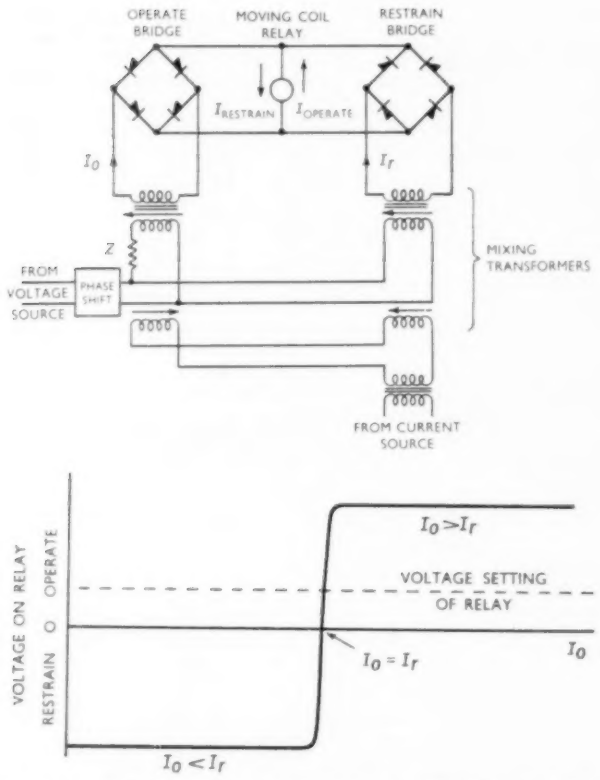


Fig. 5.—Schematic diagram and characteristic of rectifier-bridge comparator circuit.

could be used, but this offers considerably less flexibility than the power-factor relay.

The principle of the directional overcurrent or impedance relay used for distance protection of feeders is eminently suitable for measurement of the phase angle and use may be made of a rectifier-bridge comparator circuit using a moving-coil relay. The basic schematic diagram of the rectifier bridge and its characteristic are shown in fig. 5, with a typical operating characteristic for the relay in fig. 6. The rectifier bridge circuits are supplied from voltage and current transformers, through phase-shifting circuits and mixing transformers, and the sensitive moving-coil relay is used to operate an auxiliary relay to effect the tripping and alarm features. From fig. 4 it is obvious that a wide setting range is not required although it is necessary to make the relay-setting variable.

An electronic type of relay may also be used for loss-of-synchronism protection by measurement of the power-factor of the motor. This relay, the block diagram of which is shown in fig. 7, uses a square-wave generator in the voltage-transformer input circuit and a pulse generator in the current-transformer circuit. Coincident half-cycle square-wave pulses from the voltage source and once-per-cycle pulses from the current source fed into an AND unit will energize the memory circuit formed by the two NOR units and thus initiate the tripping operation. Fig. 8 shows how the pulses are matched to provide an output, while the general operating characteristic is the same as the rectifier-bridge comparator moving-coil type of relay shown in fig. 6.

A further choice of protective equipment available for the detection of loss of synchronism is the silicon controlled rectifier. In this application, the basic circuits of which are shown in fig. 9, the current-transformer input is used to give short pulses once per cycle and these pulses are compared with the voltage source as shown in fig. 10, so that the silicon controlled rectifier is triggered when the pulses coincide with the voltage wave.

With the application of any type of power-factor relay to monitor the load-angle of a synchronous motor it is always necessary to control the rate of increase of mechanical load to the motor, as a large increment of load suddenly thrown on to the motor may cause oscillation of the load-angle about its mean position for that load, owing to the inertia of the motor and its load. Should the driven load be subject to extreme fluctuations the power-factor relay may have to be set accordingly nearer to unity power-factor.

ROTOR HEATING

An additional complication is that of field failure while the motor is operating at low load. Under these conditions the motor

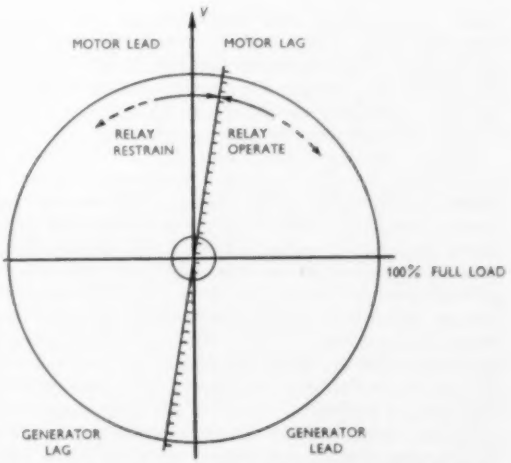


Fig. 6.—Typical operating characteristic of rectifier bridge circuit.

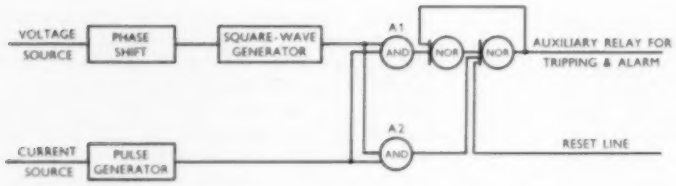


Fig. 7.—Schematic diagram of electronic relay for loss-of-synchronism protection.

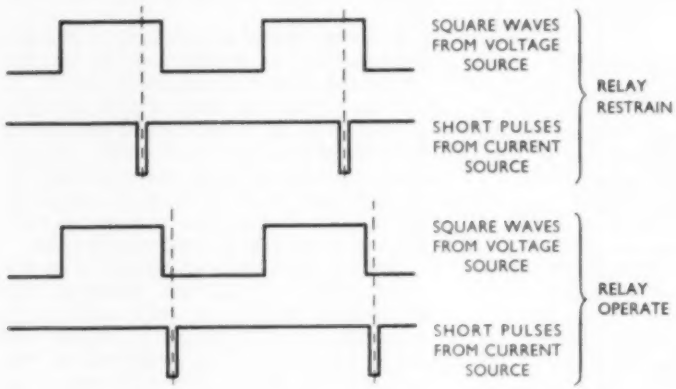

SQUARE WAVES FROM VOLTAGE SOURCE
SHORT PULSES FROM CURRENT SOURCE
RELAY RESTRAIN
SQUARE WAVES FROM VOLTAGE SOURCE
SHORT PULSES FROM CURRENT SOURCE
RELAY OPERATE

Fig. 8.—Method of matching pulses to provide relay output.

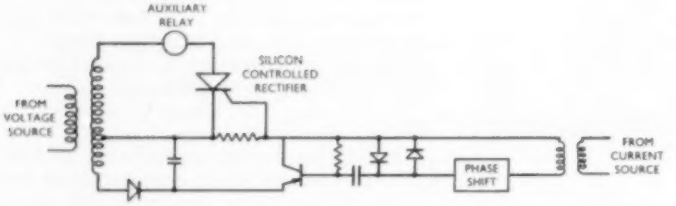


Fig. 9.—Schematic diagram of loss-of-synchronism relay incorporating silicon controlled rectifier.

could theoretically lose synchronism but remain temporarily in a safe condition as an induction motor at low slip. This condition should not be allowed to persist owing to heating, and protection is given against such an eventuality by the use of apparatus to supervise the thermal condition of the rotor.

When running asynchronously a synchronous motor has induced in its rotor a voltage at a frequency related to the speed of the motor. This voltage can cause circulating currents in the pole-face windings, which may thus be subjected to a large heating effect. In the past it has not been standard practice to advocate the use of protective equipment to supervise the rotor heating, but cases have occurred where the pole-face windings of a motor have been able to produce adequate load torque for the particular operating condition and the motor has continued to operate asynchronously for a prolonged period of time. Such fault conditions could have been detected by a rotor-heating protective system, even though the motors were not fitted with protection against loss of synchronism. A relay used to detect this heating during the running up sequence will serve to eliminate the need for a stalling relay set to cover the overall starting time of the running up sequence, giving a considerably more logical and accurate protection to the rotor.

Current practice is to use solid pole shoes, using the induced eddy currents for starting, on synchronous motors other than those with high pull-in torque or low speed requirements. Solid pole shoes have a considerably greater heat dissipation rate than laminated ones, but irrespective of the type of pole shoe and whether or not a squirrel cage winding is used, there is a certain degree of heating at subsynchronous speeds. The type of pole shoe used on any particular machine may have an effect on the control circuits during starting if a Korndorfer starting sequence is used, since it is possible to synchronize low-starting-torque motors while running at the tap voltage.

Direct temperature measurement of the pole shoes cannot be made and since there are no external connexions a resistance measurement principle cannot be

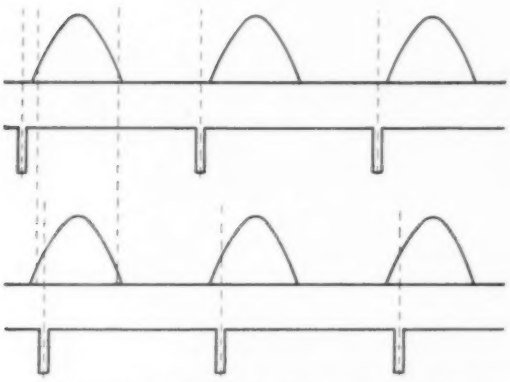


Fig. 10.—Current pulse and voltage wave comparisons.
(Top) Power factor is such that auxiliary relay does not operate.
(Below) Lagging power factor causes current pulse to coincide with voltage wave, thus operating auxiliary relay.

of reactance and thermal element resistance the curve of operation may be matched to the heating of the pole-face winding.

An alternative method is to count the number of pulses of induced voltage in the rotor circuit. The number of pulses in a given time is a function of the speed, so that at low speeds during running-up the permissible number of pulses is reached in a very short time, and at full induction-motor speed the number of pulses counted takes considerably longer. This may be done by using a stepping motor, which is merely a small synchronous motor with low inertia and high torque giving a snap action during each half-cycle. The complete revolutions of the stepping motor may be counted on a mechanical or an electrical counter which initiates an auxiliary relay when the predetermined number of pulses has been counted.

Instead of a stepping motor to count the pulses a miniature high-speed uniselector may be used which will respond to the 50 c/s impulses at the moment of starting the motor. The uniselector is used with

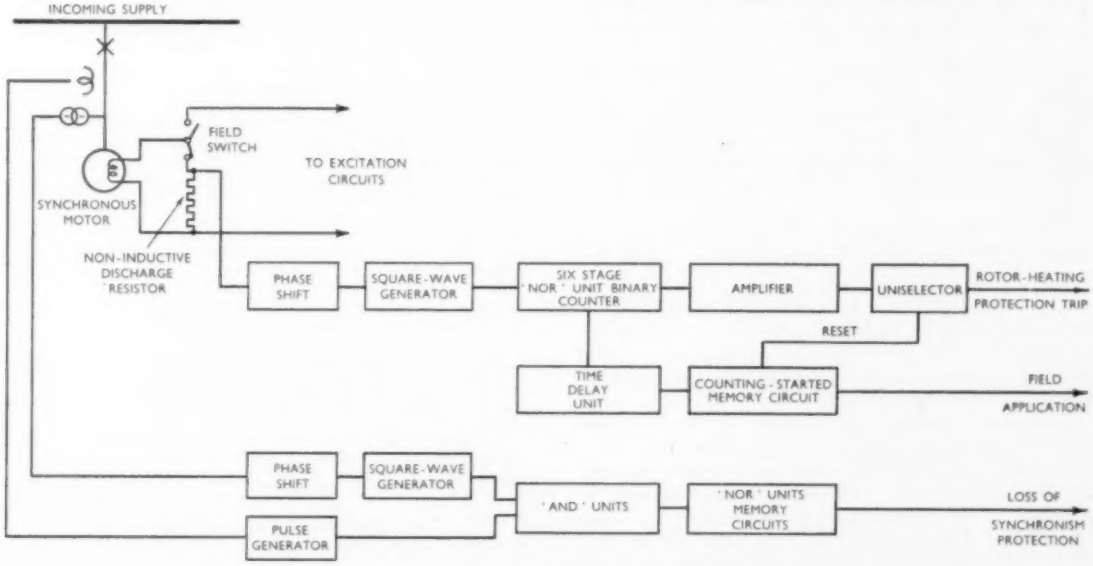


Fig. 11.—Block diagram of complete electronic control and protection scheme.

followed. Protection against rotor-heating can be given by a thermal element in parallel with a choke, the combination being fed from a current transformer in the rotor circuit. At low speeds the reactance of the choke is high and the greater proportion of the current passes through the thermal element, but as the machine increases in speed the frequency of the induced current decreases and the reactance of the choke is also decreased, resulting in an increase of current in the choke. By an appropriate combination sequence switching and with two uniselectors arranged for sequential operation the overall response is made to correspond to the rotor-heating.

The six-stage NOR unit binary counter, the first stage of which can be used for field application duty, may be used to operate a uniselector through a transistor amplifier, as an alternative system. Fig. 11 is a block diagram giving details of the complete electronic control and protection scheme covering field application, loss of synchronism and rotor-heating protection.

Materials for Thermoelectric Refrigeration

By H. J. GOLDSMID, B.Sc., Ph.D., F.Inst.P., and
R. T. DELVES, B.A., B.Sc., Hirst Research Centre.

Refrigeration by means of the Peltier effect has become practicable in recent years due to the availability of improved thermoelectric materials, notably bismuth telluride and its alloys. This article shows how these materials have been developed and outlines some of their more important properties.

INTRODUCTION.

IN 1834 Peltier discovered that the passage of an electric current across the junction between two dissimilar conductors leads to a heating or cooling effect according to its direction. The requirements for making use of the Peltier effect in refrigeration were expressed in quantitative form by Altenkirch[1] in 1911. However, it is only in the last decade that thermocouple materials have become good enough for thermoelectric refrigeration to change from a dream to a reality.

When comparing different thermocouples it is convenient to assign to each a figure of merit Z given by[2]

$$Z=\frac{(\alpha_p-\alpha_n)^2}{\left\{(\kappa_p/\sigma_p)^{\frac{1}{2}}+(\kappa_n/\sigma_n)^{\frac{1}{2}}\right\}^2} \qquad (1)$$

where α is absolute Seebeck coefficient*, κ is thermal conductivity and σ is electrical conductivity. The subscripts p and n refer to the positive and negative branches of the thermocouple.

Expressed qualitatively, equation (1) shows that good thermoelectric materials should have high Seebeck coefficients, high electrical conductivities and low thermal conductivities. This may be understood with reference to the thermojunction shown in fig. 1. The reversible Peltier cooling effect is opposed by the irreversible effects of Joule heating and thermal conduction.

Z is directly related to the coefficient of performance ϕ for refrigeration as shown in fig. 2; in this diagram ϕ is plotted against the temperature difference ΔT between the hot and cold junctions for various values of Z, the mean temperature being 20° C.

It is useful to define a figure of merit z for a single thermoelectric material as

$$z=\frac{\alpha^2\sigma}{\kappa} \qquad (2)$$

Although the figure of merit Z of a couple cannot be expressed precisely in terms of z for its two elements, it is usual for Z to lie very close to the mean of z_p and z_n.

SEMICONDUCTOR THERMOJUNCTIONS.

Insulators are useless for thermoelectric applications since, although they may have very high Seebeck coefficients, their electrical conductivities are, by definition, negligible. On the other hand, metals have relatively

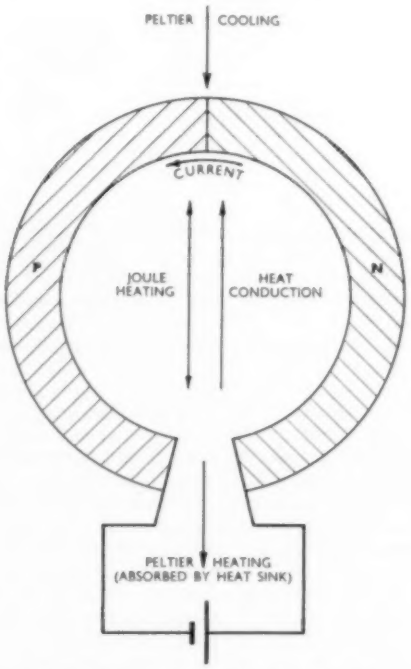


Fig. 1.—A simple thermoelectric refrigerator.

*The absolute Seebeck coefficient of a conductor is defined as the open circuit e.m.f. for unit temperature difference between the junctions of a couple consisting of this conductor and a metal with zero Seebeck coefficient. The fact that a superconductor is such a metal allows one to establish absolute values for the Seebeck coefficients of other conductors at very low temperatures. For a discussion of the determination of absolute Seebeck coefficients at higher temperatures and of the thermoelectric coefficients in general see, for example, reference 3.

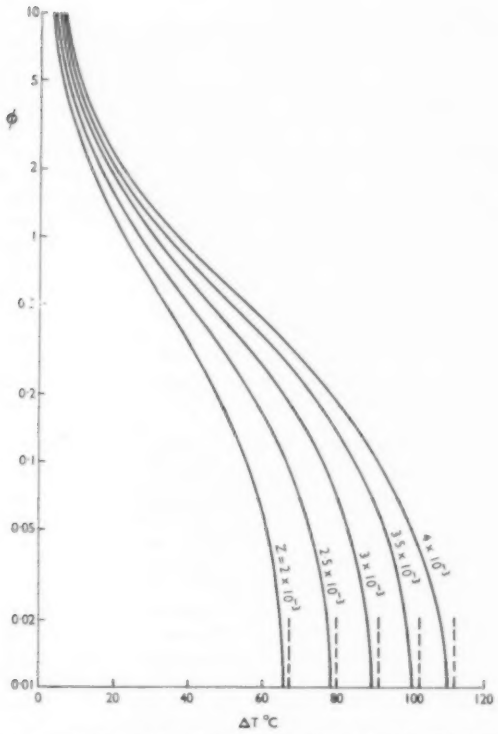


Fig. 2.—Coefficient of performance of a thermoelectric refrigerator plotted against temperature difference for a mean temperature of 20° C.

poor figures of merit since they have low Seebeck coefficients and the ratio of electrical to thermal conductivity cannot be greater than the value given by the Wiedemann-Franz law. It is found that the best compromise between a number of conflicting requirements can be achieved using certain semiconductors.

It is possible to adjust the polarity and the density of charge carriers in a semiconductor by doping. In *n*-type semiconductors the carriers are electrons and the Seebeck coefficient is negative; in *p*-type materials current is carried by holes and the Seebeck coefficient becomes positive. It is obvious that the higher the carrier concentration the greater is the electrical conductivity. However, as the carrier concentration rises the magnitude of the Seebeck coefficient falls.

Heat may be conducted through a semiconductor by the lattice vibrations and by the charge carriers. Thus the total thermal conductivity κ is the sum of a lattice component κ_L and an electronic component κ_e. κ_L is more or less independent of the carrier concentration but κ_e is approximately proportional to the electrical conductivity.*

It has been shown[4] that the figure of merit of a given semiconductor reaches its highest value when the Seebeck coefficient is brought to approximately ± 200 μV/°C. Whether the figure of merit is then useful depends on certain of the basic semiconductor parameters. The carrier mobility should be high, the lattice thermal conductivity should be low and there

*The transport of heat by bipolar thermodiffusion in an intrinsic semiconductor will be referred to later.

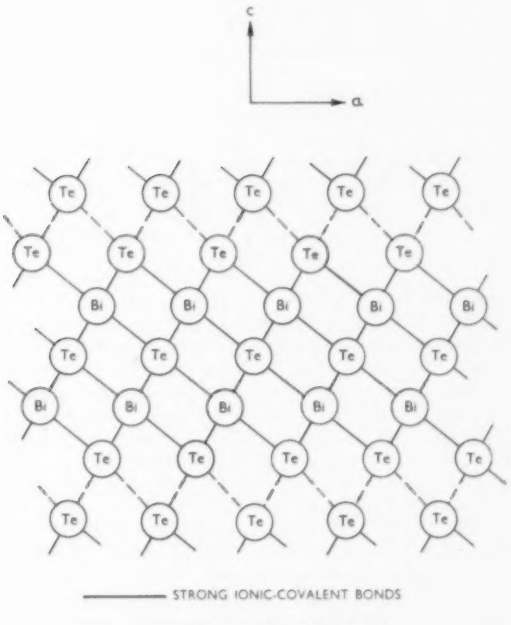


Fig. 3.—Layer structure of bismuth telluride.

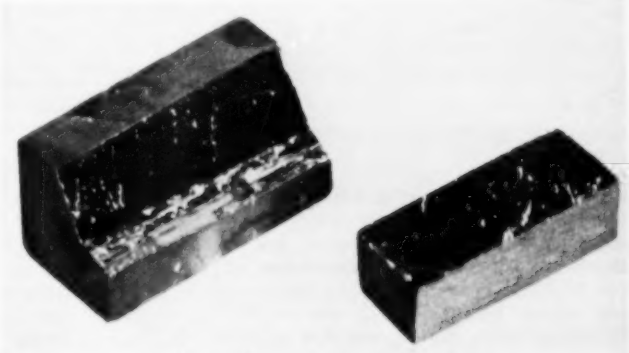
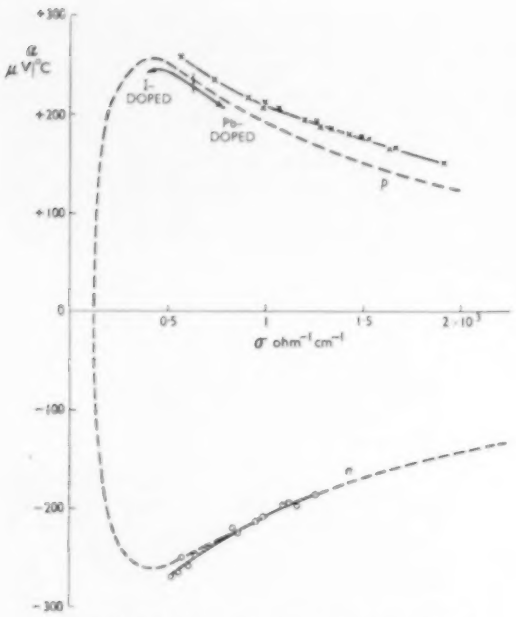
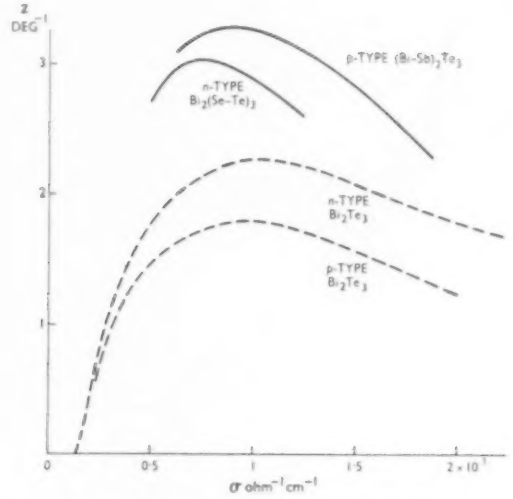


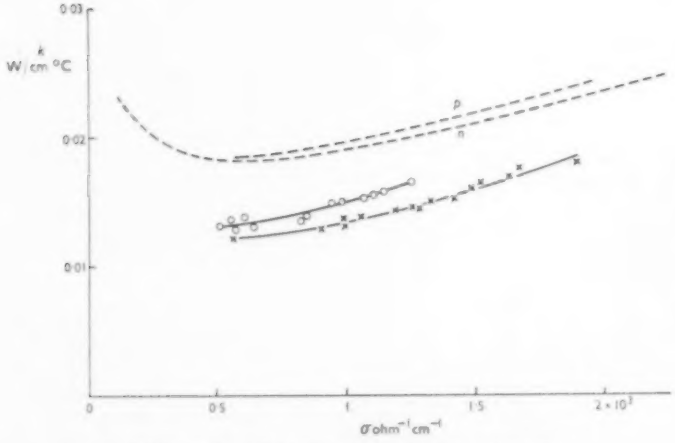
Fig. 4.—Cleavage in samples of Bi_2Te_3.
(Left) Aligned polycrystal. (Right) Single crystal.



(a) *Seebeck coefficient against electrical conductivity.*



(c) *Figure of merit against electrical conductivity.*



(b) *Thermal conductivity against electrical conductivity.*

Fig. 5.—Thermoelectric properties of bismuth telluride and its alloys at 20° C.
- - - - - - - - Bi_2Te_3.
x ———— x $(Bi\text{-}Sb)_2Te_3$ (p-type).
0———— 0 $Bi_2(Se\text{-}Te)_3$ (n-type).

should be a large density of states for accommodating the charge carriers of a given energy. These requirements are somewhat contradictory but it has been demonstrated that the best combination of properties is to be found in semiconducting compounds of high mean atomic weight [2, 4]. It was on this basis that bismuth telluride, Bi_2Te_3, was first selected. Bi_2Te_3 has since proved to be the best compound for thermoelectric refrigeration.

BISMUTH TELLURIDE.

The most important features of the crystal structure of Bi_2Te_3 are shown in fig. 3. It will be seen that there are layers perpendicular to the 'c' axis which are composed entirely of either Bi or Te atoms. The Te layers are strongly bound to the Bi layers but weakly bound to each other. Thus it is a simple matter to cleave a Bi_2Te_3 crystal in the plane of the 'a' axes but, perpendicular to this plane, Bi_2Te_3 is relatively strong.

Naturally enough, a crystal showing such anisotropic mechanical properties also displays anisotropy of its electrical and thermal conductivities. Both conductivities are greater along the cleavage planes, the anisotropy ratio being larger for the electrical than for the thermal conductivity. Since the Seebeck coefficient is isotropic it is concluded that samples will have the highest figures of merit when they are oriented so that current flows along the planes of cleavage. This does not mean that single crystals must be employed. If an ingot of Bi_2Te_3 is zone melted or directionally frozen* it is found that the cleavage planes, while by no means parallel to one another, all lie parallel to a common axis. Fig. 4 illustrates the results of cleavage for both a single crystal and for a sample cut from an aligned polycrystalline ingot produced by zone melting. The properties which will now be outlined apply to zone-melted material.

The broken curves of fig. 5(*a*), 5(*b*) and 5(*c*) show how the Seebeck coefficient, thermal conductivity and figure of merit of *p*-type and *n*-type Bi_2Te_3 vary with electrical conductivity.

On the extreme left-hand side of fig. 5(*a*) there is a region of low Seebeck coefficient and low electrical conductivity. This corresponds to intrinsic conduction for which the thermoelectric effects due to electrons and holes act in opposition. As shown in fig. 5(*b*), the same region displays a rise in thermal conductivity due to the transport of ionization energy by electron-hole pairs. It is clear that one should not use intrinsic Bi_2Te_3 in thermoelectric devices.

Fig. 5(*c*) shows that the highest figures of merit of about $2{\cdot}2\times10^{-3}$ deg^{-1} and $1{\cdot}8\times10^{-3}$ deg^{-1}, for *n*-type and *p*-type Bi_2Te_3 respectively, are achieved when the electrical conductivity is about 1000 ohm^{-1}cm^{-1}. The optimum Seebeck coefficient lies close to the predicted value of ±200 μV/°C.

ALLOYS OF V-VI COMPOUNDS.

Ioffe and his colleagues[5] first pointed out that the figure of merit of a pure element or compound could be raised by alloying it with an isomorphous material. The disturbance in the short-range order for a solid solution reduces the lattice thermal conductivity more than the carrier mobility. Thus, Bi_2Te_3 has been improved by alloying with antimony telluride, Sb_2Te_3, and bismuth selenide, Bi_2Se_3.

The replacement of more than half the Bi atoms in Bi_2Te_3 by Sb atoms is actually found to raise the hole mobility at the same time as the lattice thermal conductivity is lowered.[6] Thus, as shown in fig. 5(*a*) and 5(*b*), for a given electrical conductivity, the Seebeck coefficient of *p*-type $(Bi\text{-}Sb)_2Te_3$ is higher than for Bi_2Te_3 while the total thermal conductivity is lower. The maximum figure of merit of the alloy is about $3{\cdot}3\times10^{-3}$ deg^{-1}.

While it is possible to produce *n*-type materials with an improved figure of merit using $(Bi\text{-}Sb)_2Te_3$ instead of Bi_2Te_3, there are difficulties in doping the alloys with the higher Sb contents. No such difficulties arise if $Bi_2(Se\text{-}Te)_3$ alloys are employed. The electron mobility can be maintained at its value for Bi_2Te_3 while the lattice thermal conductivity falls by a third. The effects on the Seebeck coefficient and total thermal conductivity are illustrated in fig. 5(*a*) and (*b*). *n*-type samples having a figure of merit of $3{\cdot}0\times10^{-3}$ deg^{-1} have been prepared.

Fig. 2 shows that thermojunctions made from the best alloys should be able to give a maximum temperature depression of over 90° C at a mean temperature of 20° C. It has been found experimentally that the maximum cooling lies within about 1° C of that predicted theoretically for the figure of merit at the mean temperature.

CONCLUSIONS.

It is clear that the present-day Bi_2Te_3-alloy thermojunctions are adequate for a large number of applications particularly in such fields as the cooling of electronic equipment or of scientific apparatus. However, it is equally certain that many more applications would become possible if the figure of merit could be raised still further. While there are no theoretical limits to the value of z, our present knowledge of conduction in solids suggests that it will never exceed about 10×10^{-3} deg^{-1}. On the other hand it is expected that better materials than the Bi_2Te_3 alloys will be developed in the future. For example, Cd_3As_2 has been found[7] to give values of $a^2\sigma$ which are higher than for Bi_2Te_3 while $AgSbTe_2$ has a lattice thermal conductivity appreciably lower than for any of the Bi_2Te_3 alloys.[8] There seems to be no reason why the favourable properties of Cd_3As_2 and $AgSbTe_2$ should not be combined in some other, as yet undiscovered, compound or alloy.

*In both zone melting and directional freezing there is slow linear movement of a solid-liquid interface.

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Elastomeric and Thermoplastic Materials for Electric Cables

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UNTIL approximately twenty years ago, natural rubber was about the only material used for insulating and sheathing electric cables for building-wiring and similar purposes. During the war, when the rubber plantations in the Far East fell into Japanese hands, it was necessary for the British cable-making industry to find quickly alternative materials to natural rubber, and several synthetic substances were employed. At the same time it was necessary for radio-frequency cables to be supplied for radar use, and polythene, which was then a very new thermoplastic material which had been developed commercially only just before the war, was used as the insulation for these cables. At the end of the war, therefore, the cable industry was beginning to employ several new synthetic materials, and since that time there has been a considerable technical improvement in the quality of cables employing synthetic rubberlike insulations and sheathings and many of these new materials have now found a natural place for themselves in the field of cables. It is felt that it would be useful to review the materials in current use and explain in detail the particular characteristics of each material which make it most suitable for a particular use. The review will deal first with elastomers and secondly with thermoplastic materials.

ELASTOMERS.

These materials require to be vulcanized, or cured, so as to form them into a suitably tough and elastic condition for cable-making use. In the unvulcanized condition all elastomers are rather soft and have very little elasticity. If an unvulcanized compound is stretched it generally tends to remain in the stretched condition after the load is removed, but a vulcanized elastomeric material will retract back to near its original length when the stretching load is removed, assuming of course that the specimen is not stretched beyond its breaking point. Elastomers in common use for the manufacture of electric cables include, in addition to natural rubber, butadiene styrene, butyl rubber, polychloroprene, silicone rubber and acrylonitrile rubber.

NATURAL RUBBER.

Natural rubber has been, and still is, used extensively for both the insulation and sheathing of electric cables and it is fair to say that it has had an extremely good record of service under normal operating conditions. To a large extent it has come to be considered as the basis of comparison for all other rubber-like cable insulants. Most natural-rubber insulated and sheathed cables to British Standards are covered with compounds complying with B.S.2899, which specifies the elastomer content by volume, and also includes a number of mechanical and electrical tests.

Natural rubber, as in the case of many other elastomers, suffers from oxidation at both room and elevated temperatures, although various types of chemical substances are compounded into the rubber mix for cable-making in order to reduce this oxidation or ' ageing '. Rubber cables which are installed and operated in accordance with the Wiring Regulations of the Institution of Electrical Engineers achieve a maximum conductor temperature of about 50° C when loaded in accordance with the I.E.E. current ratings, but for other purposes it is possible to operate natural-rubber cables at temperatures up to 60° C and with the present-day modern rubber compounds a fairly long life of something like twenty years could be expected at this operating temperature. Rubber has excellent low-temperature characteristics and remains quite flexible at temperatures as low as —40° C. The oil and solvent resistance of natural rubber is not particularly good, but for the majority of installations rubber insulation or sheathing does not usually come into contact with such substances. Natural rubber also is combustible and once ignited burns quite well, leaving behind an electrically conducting carbonaceous deposit. However, under normal installation conditions, even the poor fire-resistance of natural rubber is not an extremely serious hazard.

From the electrical point of view, natural rubber has stood the test of time as an insulant for building-wiring cables for very many years. The insulation resistance of such an installation is generally quite high and remains so for a very long time, except where part of the installation is operating under humid conditions in which case some falling off in electrical properties is expected. Rubber compounds have been used for many years for the insulation of power cables required to operate at voltages up to 11 kV and have provided a useful type of high-voltage insulation of flexible trailing cables as used, for example, in certain quarries.

National specifications of some other countries have for some considerable time accepted natural-rubber insulation for even higher voltages.

Butadiene Styrene.

This class of synthetic rubber was the one that first appeared on a large scale in Great Britain during the war, when supplies of natural rubber from the Far East became difficult and the butadiene styrene (S.B.R.) was in those days referred to as G.R.—S. which was the American nomenclature for 'Government Rubber—Synthetic'.

There is probably more S.B.R. employed in the rubber industry as a whole than any other synthetic rubber, for it is used very extensively in the manufacture of motor-car tyres. Until recently, S.B.R. was obtainable only from abroad (mainly U.S.A.) but it is now available from plant installed in the United Kingdom. By slightly modifying the production techniques it is possible to vary the properties of the S.B.R., and the particular grades used for electric-cable insulating compounds may not always be the grades which are used for motor-car tyres. Generally speaking, insulation compounds made from S.B.R. are not as good as those made from natural rubber with regard to mechanical and electrical properties. The tensile strength of an insulating compound based on S.B.R. would normally be only 60-70% of that of a compound containing a similar quantity of natural rubber, and even if blends of natural and S.B.R. rubbers are produced the resultant compound is inferior to all-natural rubber. In the same way the electrical insulation resistance of S.B.R. is a little less than natural rubber, but for ordinary building-wiring purposes compounds produced from S.B.R. would be quite satisfactory. As a basic raw material S.B.R. tends to be cheaper than natural rubber and the characteristics of S.B.R. from batch to batch are much more consistent than those of natural rubber which, it must be remembered, is a natural product over which there is less technical control. At the present differential in raw material costs there is a slight economic advantage in employing S.B.R. insulation or sheathing, but the cable user in accepting the lower price must also be prepared to accept lower physical and electrical properties. At the present time, B.S.2899 allows synthetic rubber to be employed in a mixture with natural rubber, but the physical and electrical requirements of this British Standard at the moment preclude the cable-maker from using a sufficient proportion of S.B.R. to make the resultant compound very much cheaper. S.B.R. is very similar to natural rubber compound in its resistance to oil, solvents and fire, and in its maximum operating temperature.

Butyl Rubber.

The major use for this synthetic rubber so far has been in the manufacture of motor-car inner tubes, but it does have some superior properties which make it worth while considering for cable insulation or sheathing, although at the same time there are a number of other properties which must be carefully considered as these are inferior to those of natural rubber compounds.

The main claim of butyl rubber over natural rubber is in its better ageing characteristics at elevated temperatures; a cable insulated with a butyl compound can operate continuously at 85° C. Butyl rubber also shows a marked improvement over natural rubber in ozone resistance. In this way it has the feature of being a good insulation in high-voltage cables where there may be excess ozone and its ozone resistance could also help in outdoor ageing in ultra-violet sunlight conditions. In this respect, natural rubber is very poor and it is well known that if a natural rubber compound is exposed to ozone or strong sunlight the surface of the rubber crazes and cracks, particularly if the compound is under any mechanical stress.

Electrically, butyl rubber is as good as, or somewhat better than, natural rubber as insulation under normal conditions, but in moist conditions, or in conditions where the cable is totally immersed in water, butyl rubber shows a considerable improvement over natural rubber compounds. Compounds made from butyl rubber are mechanically inferior to natural rubber and a normal electric cable insulation would have a tensile strength of only about one-half of that of natural rubber compound to B.S. 2899. Butyl rubber is affected by some oils and solvents in the same way as natural rubber and is just as combustible. Although the butyl elastomer is cheaper than natural rubber and S.B.R., the complete compounds which are employed for cable-making are generally more expensive and the application costs are higher so that this tends to restrict the use of butyl to those cables where it is possible to take advantage of the better characteristics.

Polychloroprene.

Although cable manufacturers experimented with this synthetic rubber before the war, it was not seriously employed for cable-making until the shortage of natural rubber in the war and it was then introduced into the industry under the trade name of 'Neoprene'. This designation has now tended to be replaced by P.C.P. (polychloroprene). P.C.P. is particularly superior to natural rubber, S.B.R. and butyl rubber in its resistance to oil and burning, and when properly compounded and black in colour, to weathering. P.C.P. has thus found a very important place for itself as a sheathing material for cables which may be insulated with other sorts of rubber compounds but where oil resistance and fire resistance is important. For a number of years all colliery flexible trailing cables used by the National Coal Board underground have been sheathed with p.c.p. in view of the excellent fire resistance. If p.c.p. is subjected to a flame from some other source the heat of the flame will cause the polychloroprene to decompose and evolve a large quantity of chlorine gas which will then blanket the flame and prevent oxygen from the atmosphere from allowing the fire to continue.

In its heat resistance, p.c.p. is only very slightly

better than natural rubber in that the maximum continuous operating temperature is around 70° C. In this respect there is often the mistaken idea that because p.c.p. is a fire-resistant material it must also be a good heat-resistant material. Nevertheless, the compound can for very short periods be subjected to quite high temperatures when used for such purposes as an insulation for coil-end flexibles which have to be capable of withstanding oils and solvents in varnishes with a subsequent baking process, although the finished coil should not normally be allowed to operate at more than 70-75° C. If p.c.p. cable-making compounds are operated continuously at higher temperatures, it is found that the compound hardens considerably and there is danger of cracking if the cable is bent, and, if the conditions are sufficiently severe, chemical degradation sets in. While all the previously mentioned rubbers are excellent at low temperatures, p.c.p. is not particularly good and unless very specially compounded it is not really suitable for temperatures much lower than — 20° C owing to the stiffening of the compound at low temperatures.

From the electrical point of view, p.c.p. is very poor and has an insulation resistance of something like 1/500th that of natural rubber. It is quite suitable for the insulation of coil-end flexibles as these leads are only employed in very short lengths, but if a composite insulation is constructed by means of applying first to the cable conductor a thin insulation of natural rubber compound followed by a somewhat similar thickness of p.c.p. compound, then a composite insulation with extremely useful properties results. This composite insulation has fairly good electrical properties in that the insulation resistance is only about one-half that of natural rubber, but the real advantage is in that the insulation is fire resistant which makes it very useful for wiring in such installations as railway signalling cabins where it is most important to avoid the spread of any fire along large bunches of cables.

Sometimes, however, p.c.p. is used as an insulation without the natural rubber layer for a special type of aircraft wiring cable where the conductor is first covered by a layer of glass fibre over which the p.c.p. is applied. Because of the relatively short life of aircraft wiring (it does not usually have to last twenty years or more as in the case of building wiring), the operating temperature of the cable is allowed to rise to 90° C. This cable is oil and fire resistant.

Silicone Rubber.

Silicone rubber compounds are well known for their good heat resistance in a number of mechanical applications such as gaskets, and for the last ten years or so silicone rubber compounds have been employed in Great Britain for the insulation of electric cables which have to operate at high temperatures. The material is very expensive compared with the other elastomers under review and therefore its use is restricted to those situations in which one can take full advantage of its very superior resistance to ageing at high temperatures and, possibly less frequently, of flexibility at very low temperatures. For continuous use, silicone rubber as an insulant can be operated at 150° C, but for short periods silicone rubber cables can be operated at up to about 200° C, or even more, but of course the higher the temperature the shorter the life.

The early silicone rubber compounds were rather weak mechanically, but compounds now available give values approximating to those required by B.S. 2899 for natural rubber. Very often, silicone-rubber-insulated conductors are covered with a spiral wrapping of asbestos, which is then protected by a Fibreglass braid saturated with high-temperature varnish, often of the silicone class. Silicone rubber is substantially similar to natural rubber in its resistance to oil so that precautions must be taken to protect the insulation where silicone-rubber cables are used, for example, on or around aircraft engines. This is usually done by selecting a special type of oil-resistant varnish which is lacquered on to the overall glass braiding.

Although silicone rubber is slightly better than natural rubber in fire resistance, it will burn if subjected to an external source of flame. The resulting ash is an insulant if not disturbed, whereas the ash from other elastomers is of an electrically conducting nature.

Acrylonitrile Rubber.

This elastomer has so far had very little application in the electric cable-making industry because its electrical properties are poor. Conventional compounds based on this elastomer have good physical properties and are extremely resistant to mineral oils and many solvents, such as petrol. More recently interest has been shown in vulcanized blends of polyvinyl chloride (p.v.c.) and butadiene acrylonitrile. These blends (p.v.c./acrylonitrile) are generally similar in properties to p.c.p. but have the advantage that in colours other than black their resistance to weathering is superior to that of p.c.p.

Thermoplastics.

Thermoplastics, as the name implies, are materials which become more plastic or softer as the temperature increases. These materials, unlike elastomers, do not require to be vulcanized. The normal method employed for applying the material to the cable is for the thermoplastic to be extruded on to the wire or core in a very soft condition at an elevated temperature. The covering is then cooled by passing the cable through water so that for normal subsequent operating temperatures the covering is hard and tough enough to withstand ordinary operational hazards. Thermoplastic materials in common use for the manufacture of electric cables include polyvinyl-chloride, polythene, polytetrafluorethylene (p.t.f.e.) and nylon.

Polyvinyl-Chloride.

This is the most well known and widely used alternative to natural rubber for electric cable insulation and sheathing. The material was available on a

small scale before the war and was investigated for cable use. A small amount of p.v.c. wiring was actually installed in various parts of the world, but it really came to the fore during the war when an alternative had to be found for natural rubber.

P.V.C. compounds can have widely differing properties depending upon the manner in which the compound is formulated; such compounds consist of a blend of polymer, plasticiser/s, stabiliser and lubricant and, when necessary, fillers and/or pigments.

P.V.C. compounds of the type normally employed for producing ordinary building-wiring cables to B.S. 2004 are made in accordance with the requirements of B.S. 2746 which specifies the physical and electrical characteristics of both insulations and sheaths.

For general wiring purposes p.v.c. compounds are inferior to natural rubber compounds in some electrical properties and the insulation resistance of such compounds is less than that of natural rubber. However, in breakdown strength, p.v.c. compounds are reasonably good and the values obtained are not much less than those obtained with natural rubber. Wiring installations making use of general-purpose p.v.c. are able to operate continuously at temperatures up to about 70° C, but if heat-resisting p.v.c. is used the operating temperature can be increased to 85° C.

P.V.C. is thermoplastic and therefore its softness and flexibility will vary with changes in temperature, but its behaviour at any temperature will depend on its composition. As the temperature falls, p.v.c. becomes harder and ultimately quite brittle and when installations are being carried out at temperatures below freezing point (0° C) care should be taken in handling the cable. If specially designed compounds are used a better performance can be obtained at low temperatures. Generally speaking, however, compounds which are flexible at low temperatures are softer at ordinary temperatures than general purpose compounds and are more easily deformable, particularly as the operating temperature increases.

Operation at high temperatures involves three factors :

1. Softening and deformation under load;
2. Volatilization of plasticiser;
3. Thermal degradation of the p.v.c. compound.

In more detail:

1. All p.v.c. compounds become softer as the temperature increases. Reference has been made to maximum temperatures for continuous operation for general purpose and for heat-resisting p.v.c. These temperatures can be exceeded for shorter service periods, provided the cables are installed in such a way that they are not subjected to sufficient mechanical pressure to cause an unacceptable amount of deformation.
2. The plasticisers in conventional p.v.c. are more or less volatile and operation at temperatures above the maximum of 70° C will result in reduction of flexibility to an extent which will depend on service conditions.
3. By employing special plasticisers and stabilising systems it is possible to obtain a p.v.c. compound which retains a larger proportion of its initial physical characteristics, e.g. flexibility, when subjected to high temperature. The recommended maximum operating temperature for this type of compound is 85° C for long service, but if the required life is relatively short, say four to five years, then the operating temperature can go up to 105° C. This type of compound is finding considerable use in coil-end flexibles which, after fitting to the component, are required to undergo varnish impregnation and baking for a few hours at up to 160° C. A heat-resisting compound will withstand such treatment and still remain flexible whereas a conventional compound would become quite hard and liable to crack on bending.

One of the excellent properties of p.v.c is its good fire resistance which makes it useful for wiring in signal cabins, telephone equipment, etc. where it is desirable to restrict the spread of fire. At room temperature, p.v.c. compounds are oil and solvent resistant and resistant to many acids, but as the temperature increases so the resistance to the various substances falls off until at temperatures above 70° C many p.v.c. compounds are not entirely suitable for use, for example, in transformer oil. However, by the selection of the right type of plasticiser, it is possible to formulate p.v.c. compounds which can operate for many years in hot oils so that special p.v.c.-insulated cables are quite commonly used as connexions inside oil-filled transformers.

Polythene.

This material, which was a British development, was first investigated for electric-cable use just before the war, and it was soon found that it had considerably better high-frequency electrical characteristics than anything which had previously been available. Thus with the development of radar equipment and the call for special aerial leads, polythene soon came into use at the beginning of the war, and for a time the majority of polythene produced in Great Britain was absorbed by the wartime cable industry.

Polythene is used instead of p.v.c. mainly on account of its excellent electrical properties. A decision to use it instead of p.v.c. or other thermoplastic materials must carefully take into account some of its shortcomings. Polythene has a rather sharp melting point around 110° C whereas p.v.c. softens gradually and never drips off the wire in a semi-liquid form as can polythene. It is important, therefore, that any cable insulated with polythene must not be allowed to reach a temperature of more than 100° C otherwise there is every possibility of failure.

Generally speaking the majority of power wiring insulated with polythene is run in accordance with the current ratings in the Wiring Regulations of the Institution of Electrical Engineers, which result in a maximum conductor temperature of 50° C so that there is a reasonable factor of safety. Polythene is

employed, however, for the insulation of power cables at low voltages and at high voltages up to and over 11 kV and for this type of cable the maximum loading on the cable is limited so that under short-circuit conditions the maximum temperature of the insulation does not exceed 90° C in order to have a small allowance in hand.

Polythene is excellent for low-temperature resistance and can operate at the lowest temperature normally encountered anywhere in the world. There have been developments for improving the high-temperature operation by subjecting the polythene insulation once it has been applied to the conductor to a high-energy gamma-ray source and this irradiation can change the molecular structure of the polythene so that its operating temperature can safely be increased by another 40° C or so. However, if the irradiated polythene were to be operated continuously near its new maximum temperature there are other complications which arise from the fact that at this elevated temperature the polythene does not soften but tends to decompose and oxidize badly, with the result that the electrical properties of the cable can suffer severely.

Similarly, 'high density' polythenes produced by the 'Ziegler' process have an increased softening point but full advantage cannot be taken of continuous higher operating temperatures since these polythenes suffer from deterioration at elevated temperatures in the same way as irradiated polythene. Irradiated and high density polythenes could, however, be of some use for insulating cables which have to withstand heavy overload currents resulting in high conductor temperatures for short periods.

Polythene is resistant to many oils and solvents at room temperatures, but at higher temperatures the resistance falls off considerably. It is sometimes necessary to protect a polythene core by means of a sheath of a material such as p.v.c. if there is the possibility of certain solvents being present, although of course, even at higher temperatures as mentioned above, p.v.c. may not necessarily be resistant to some solvents and oils.

Polythene burns very readily and has the undesirable characteristic of dripping molten burning material when it burns, so that great care must be taken to see that bare polythene core is not employed where there is a fire risk. Polythene compounds can, however, be formulated by the addition of various chemical compounds so that they become flame retardant. The incorporation of these chemicals tends to lower the electrical properties.

Polythene has poor ultra-violet-light resistance and if ordinary polythene is subjected to strong sunlight, photo-chemical decomposition of the material can take place. This results in severe breakdown of the surface of the cable and cracking can eventually take place right through to the conductor. It has been found, however, that if carbon black of fine particle-size is uniformly dispersed within the polythene compound at the rate of about 2% by weight of carbon black, then the resistance to ultra-violet light is considerably improved. Many high-frequency cables of the radio-relay and television-relay type are now installed out-of-doors in tropical sunlight, and with the incorporation of the carbon black in the sheath a long life appears to result.

Polytetrafluorethylene (P.T.F.E.).

In the case of elastomeric cable-making materials, silicone rubber is available at a high price for high-temperature conditions and in the thermoplastic range of materials p.t.f.e. is available. P.T.F.E., sometimes known under the trade names of 'Fluon' or 'Teflon', is extremely expensive, costing £3-£5 per lb.

Electrically, p.t.f.e. resembles polythene, as it has an extremely low loss and is ideal for high-frequency use, but whereas polythene has a poor temperature limitation, p.t.f.e. is able to operate for long periods at temperatures up to 250° C. Incidentally, this temperature should not be greatly exceeded, particularly in confined space, because at temperatures over 250° C to 300° C p.t.f.e. can decompose and give off toxic fumes.

Until the present time, p.t.f.e. has been used mainly in relatively short lengths for hot spots in aircraft and in ballistic missiles, but as the use of this material becomes more widespread, possibly in non-electrical industries, the price, which has already been reduced from the early days, may be reduced even more and possibly p.t.f.e. may one day be no more expensive than silicone rubber.

The method of applying p.t.f.e. to cable conductors presents a number of difficulties, so that the cable-making operation itself is costly, but nevertheless, even with the present price of the completed p.t.f.e.-insulated wire, the high cost is often warranted because of the excellent heat resistance.

Nylon.

Nylon (chemical name—polyamide), is finding an increasing use as a sheathing material for certain types of cables. If nylon is extruded on to the cable core in a molten state and then stretched so as to elongate it considerably before it has become completely cooled, the tensile strength of the material increases tremendously, so that it is possible to apply an extremely thin but very strong extruded covering to certain kinds of cable. Very many thousands of miles of field telephone cable for Army use have been manufactured with an insulation of polythene followed by a thin extruded sheath of nylon which is only 0.004 in. thick. Such nylon sheathing will withstand the rough mechanical handling normally associated with field telephone cable. Although nylon itself is not a particularly good insulator its main purpose is to protect the polythene insulation underneath. If nylon is applied to cables as a sheath in greater thicknesses, the cable becomes rather inflexible owing to the very stiff nature of nylon. Nylon has good ageing properties and the type used for electric cables can be run continuously at temperatures up to about 100° C. It is very resistant to many oils and chemicals.

Type 2 Diesel-electric Locomotives for British Railways

By R. H. BRYANT, B.Sc. (Eng.), A.C.G.I., A.M.I.E.E.,
Traction Division, Engineering Group.

THE British Transport Commission's programme for the modernization of British Railways includes the electrification of heavily loaded routes and the replacement of the steam locomotive by diesel power elsewhere on the system. Much of the new equipment for these purposes has already been described in this Journal, an exception being the type 2 diesel-electric locomotive (fig. 1), for which G.E.C. is supplying a total of 127 electric power equipments.

Fig. 1.—B.R.C.W./G.E.C. Type 2 Diesel-electric Locomotive.

Of these, the first 58 type 2 locomotives, which are already in service, were built by North British Locomotive Co. Ltd., and are fitted with 1100 h.p. M.A.N. engines. The electrical equipment for these units is broadly similar to that of the type 1 locomotive described in the *G.E.C. Journal*, Vol. 25, No. 4, October 1958. The present article describes the second batch of 69 locomotives, which will shortly be handed over for service. These are being built by the Birmingham Railway Carriage and Wagon Co. Ltd. and incorporate 1250 h.p. Sulzer diesel engines and an improved electrical transmission system.

The locomotives are geared for a maximum speed of 90 mile/h and, in view of the importance of having maximum power available at the higher speeds for operating passenger trains, the transmission has been designed to absorb the full engine output up to 80 mile/h. Furthermore, as will be seen from the tractive effort/speed curve (fig. 2), the amount of engine unloading which occurs between this point and the maximum speed is not such as to affect significantly the performance of the locomotive.

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employed, however, for the insulation of power cables at low voltages and at high voltages up to and over 11 kV and for this type of cable the maximum loading on the cable is limited so that under short-circuit conditions the maximum temperature of the insulation does not exceed 90° C in order to have a small allowance in hand.

Polythene is excellent for low-temperature resistance and can operate at the lowest temperature normally encountered anywhere in the world. There have been developments for improving the high-temperature operation by subjecting the polythene insulation once it has been applied to the conductor to a high-energy gamma-ray source and this irradiation can change the molecular structure of the polythene so that its operating temperature can safely be increased by another 40° C or so. However, if the irradiated polythene were to be operated continuously near its new maximum temperature there are other complications which arise from the fact that at this elevated temperature the polythene does not soften but tends to decompose and oxidize badly, with the result that the electrical properties of the cable can suffer severely.

Similarly, 'high density' polythenes produced by the 'Ziegler' process have an increased softening point but full advantage cannot be taken of continuous higher operating temperatures since these polythenes suffer from deterioration at elevated temperatures in the same way as irradiated polythene. Irradiated and high density polythenes could, however, be of some use for insulating cables which have to withstand heavy overload currents resulting in high conductor temperatures for short periods.

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Electrical Engineer, Eastern Region, to whom the first twenty of the earlier locomotives were supplied. The new locomotives are destined for service in the Scottish, North Eastern and London Midland Regions, but all the locomotives will be commissioned at Doncaster before being transferred to their operating region.

To suit the varying operating requirements of the Regions, there are certain detailed differences between the locomotives; for example, the 23 for the Scottish Region will be fitted with tablet pick-up equipment, while the nine for the North Eastern Region will be without train-heating boilers. Leading particulars of the locomotives are given in the table below.

Axle arrangement	Bo-Bo
Top speed	90 mile/h
Unloading speed	80 mile/h
Starting tractive effort ...	40 000 lb
Continuous - rated tractive effort	25 000 lb at 14 mile/h
Weight with full fuel supplies	73½ tons
Weight with two - thirds fuel supplies	72 tons
Fuel capacity, engine ...	500 gal
Fuel capacity, train heating...	100 gal
Water capacity, train heating	550 gal
Wheel diameter	43 in.
Bogie wheel base	10 ft
Bogie centres	29 ft
Length over body	48 ft 3 in.

The locomotives are designed for the operation of up to three units in multiple, under the control of one driver.

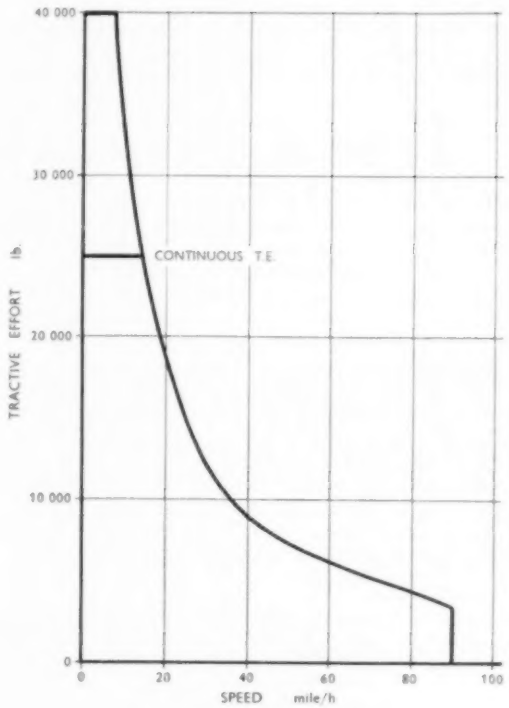


Fig. 2.—Tractive effort/speed curve.

GENERAL CONSTRUCTION.

The locomotives are of the double-cab type with a full-fronted cab at each end. Construction is generally of welded steel with the body sides acting as stress-carrying beams which, with the underframe, support the weight of the power-unit and auxiliaries. The engine room has been provided with a translucent roof trap, moulded in Fibreglass-reinforced polyester resin and fitted with quick-release fasteners, to avoid any necessity for staff to work on the roof of the locomotive, thus precluding any potential danger from high-voltage overhead contact wires.

The bogies have fabricated steel frames with equalizing beams and swing bolsters. Primary and secondary suspension is by nests of coil springs, while the bolsters are also equipped with a shock absorber at each end, provision being made for the fitting of a second shock absorber if required. Roller-bearing axle-boxes are fitted, with manganese steel liners in the horn guides. An improved design of traction motor air bellows has been fitted which, by means of quadruple springs, ensures that the bellows remain in contact with the air ducting at all times, thus minimizing any possibility of dirt entering the traction motors. Each bogie is provided with four Westinghouse 8 in. brake cylinders operating through clasp rigging, and sand boxes are fitted to supply all wheels.

Brake control is standard, with the locomotive air brakes normally operated through the proportional valve from the vacuum train brake control, but with provision for applying a straight air brake on the locomotive if desired. The controller is equipped with an anti-slip device, while the sanding is operated by pushbutton control. The air control piping, together with all Westinghouse E.P. valves, etc., has been installed in a small area of the engine room and situated against the body side to provide free access to all items of equipment.

Layout of equipment follows closely that of the earlier locomotives. A central full-width engine compartment provides convenient access down each side of the locomotive. The radiator panels are situated immediately behind No. 1 cab and are side-mounted with a vertical fan exhausting through the roof. The oil-fired train-heating steam generator is installed in a separate compartment adjoining No. 2 cab, with its fuel tank mounted under the roof of the boiler compartment. The batteries are carried in two roll-out boxes situated at each side of the underframe, while the main fuel and boiler water tanks are also underframe-mounted.

Particular care has been taken to ensure that there is no possibility of oil accidentally spilled from the interior of the locomotive penetrating to the underside of the underframe, thus preventing any likelihood of

oil entering the traction motors. Furthermore, on this locomotive the design of the underframe has been correlated with the engine speed to a point where vibration in the structure has been kept to an absolute minimum. Maintenance costs on auxiliary equipment should therefore be low.

Although no engine silencer is fitted on these locomotives, since the exhaust turbo-charger is expected to provide sufficient silencing, provision has been made in the locomotive structure to accommodate an external silencer of the box type if subsequently required.

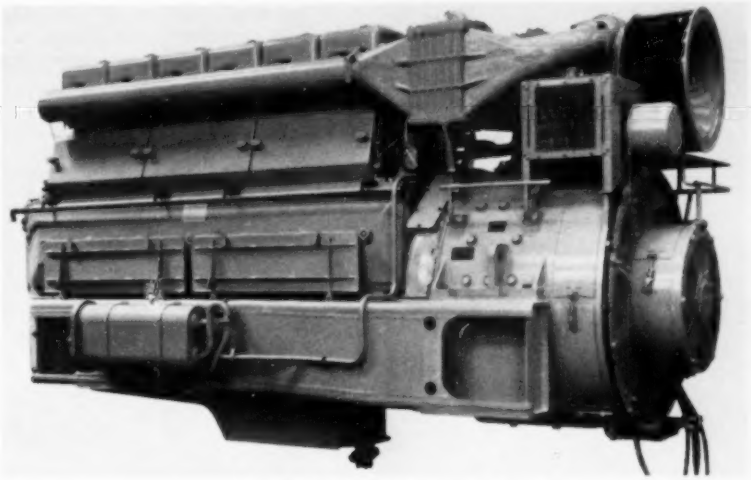


Fig. 3.—Engine/generator unit.

DIESEL ENGINE.

The locomotives are powered by the Sulzer 6LDA28B 6-cylinder diesel engine, pressure charged to 1250 h.p. at 750 rev/min by the addition of simple charge-cooling arrangements.

Engine speed is controlled pneumatically by a self-lapping air valve incorporated in the driver's master controller, acting on the engine governor. To avoid overloading the engine and to ensure that the engine output is utilized to best advantage at all speeds, the field strength of the main generator is varied by a regulator which is servo-operated from the engine governor, thus providing automatic adjustment of output.

Arrangements for protection of the engine against failure of oil or water circuits and against overloads, etc., are described later. Automatic fire alarms ring in the cab if the engine-room temperature exceeds a safe value, enabling the driver to operate built-in CO_2 fire-protection equipment.

The engine incorporates all the well-known Sulzer design features including: stepless pneumatic control of engine speed, engine-mounted oil/water heat exchanger for control of lubricating oil temperature; and a separate motor-driven combined pump set for circulating cooling water and lubricating oil as well as supplying fuel under pressure to the engine. This ensures that coolant circulation is commenced before the engine can be started, and can also be continued after it is shut down.

A single inter-cooler is fitted directly into a wide portion of the induction manifold between the pressure-charger and the engine, thus making it an integral part of the engine. Cooling water is derived from the main engine cooling circuit, thereby eliminating the need for a separate water circuit with additional piping, radiator and pumps.

At the rated output of the engine, the b.m.e.p. is 165 lb./in.^{2} and the mean piston speed 1770 ft/min. Specific fuel consumption is about 0.37 lb/b.h.p./min at full load and about 0.36 at half load, while the one hour rating of the engine is 1375 h.p. at 750 rev./min.

MAIN AND AUXILIARY GENERATORS.

The main generator is a 10-pole single-bearing machine with four field windings (separately excited, self-excited, reverse series and starting). It has a fabricated frame and is rated at 805 kW, 1940 A at 750 rev/min.

Both main and auxiliary generator armatures are mounted on a common cast-steel hub, which is bolted solidly to the engine crankshaft flange, and is carried in a single roller bearing at the outer end. Advantage has been taken of the necessarily large diameter of the medium-speed main generator partially to recess the auxiliary generator into it, and so keep the overall length of the set to a minimum.

To facilitate maintenance of the brushgear, the brush holders are mounted on a rocker which can be revolved

through a gear drive so that they can be brought to a convenient position for servicing. Both machines are self-ventilated by one fan on the main armature which discharges the cooling air downwards to atmosphere through trunking in the underframe. Provision is made on the fan disc for barring the engine by hand.

The 57 kW auxiliary generator is a 6-pole machine whose output is maintained at a substantially constant voltage of 110 by means of an automatic voltage regulator.

loading on the auxiliary generator at low engine speeds.

Two exhausters are driven by integrally-mounted G.E.C. motors, these again being two-speed machines, normally running at the lower speed to maintain vacuum, but being speeded up for brake release under the control of the brake valve contacts. Air for the locomotive brakes and control is provided by a motor-driven compressor.

The engine water and oil pumps are driven by a

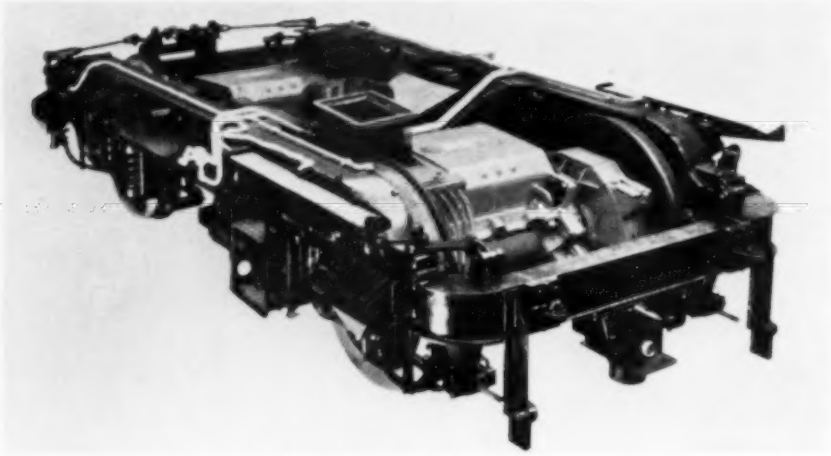


Fig. 4.—Bogie for Type 2 locomotive

TRACTION MOTORS.

Four axle-hung traction motors are connected in parallel across the output of the main generator and drive the axles through resilient gears. These machines are force-ventilated 4-pole series motors and are similar to those fitted to the N.B.L./G.E.C. type 2 locomotives.

As in the case of the main generators, the brushgear can be rotated to enable all service attention to be given from below the machines, and the motor noses are resiliently supported. The continuous rating of each machine is 236 h.p. 485 A, 415 volts, and the gear ratio is 17/60.

AUXILIARIES.

The radiator fan is driven by a 16 h.p. motor having two speeds (840 and 1500 rev/min) under thermostatic control, the higher speed being obtained by a field tapping.

Twin blowers, each supplying cooling air to two traction motors, are driven by a single motor, which is also a two-speed machine running as a compound motor at slow speed and a series machine at high speed. Both for this machine and the radiator fan motor, high-speed running is obtainable only after a certain controller position has been reached, thus reducing the

single motor which operates from the battery for engine starting purposes, and can maintain circulation after the engine has stopped. Both exhauster sets are mounted in the tunnel under the radiator ducting, one on each side, while the air compressor and the twin blower units are installed between the radiator and the fan end of the engine. The engine pump unit is mounted transversely between the blower unit and the engine.

CONTROL SCHEME.

The scheme is designed to ensure that the engine output is absorbed by the transmission over the widest range of locomotive speed, without overloading the engine within this range, and this is accomplished by a combination of generator voltage control and motor field control.

Generator excitation is obtained by a combination of the separately excited and self-excited fields, and the output is controlled by a resistor in the separate field circuit which is adjusted by the load regulator under the control of the engine governor.

The self-excited field is so proportioned as to follow the separately excited field and provide a reflected type of field variation which, while giving effective control, reduces the size of the load regulator. A reverse series

field gives a slight decompounding effect and is also used in conjunction with the short-rated starting field when motoring the engine from the battery for starting purposes. Provision is made on the underframe for connexion of an outside supply for engine starting in the case of a discharged battery.

Each traction motor is protected by an overload relay and a contactor, and in the event of an overload trip the main-generator separate-field excitation is also removed, thus considerably easing the load on the contactors. Provision is made for cutting out any individual motor, permitting the operation of the locomotive on the remaining three motors.

Motor field weakening is introduced automatically in three stages which are outside the driver's control. It is initiated by a relay in the separate field circuit of the main generator, operating in conjunction with the load regulator in such a way as to ensure that the field-divert contactors do not close until the generator voltage has been reduced to a suitable value. This limits the current in the traction motors and avoids overloads on the engine. Backwards transition is also automatic on a rising load such as would be occasioned by an increase of track gradient.

Fig. 5.—Control equipment cubicle.

PROTECTION AND FAULT INDICATION.

Protective devices are arranged to shut-down the engine in the event of loss of lubricating oil pressure or failure of cooling water circulation, and to reduce it to idling speed in the event of failure of control air, overload in any traction motor, or earth fault in motor or generator. These are supplemented by a number of additional features in the way of fault indication.

An alarm panel in each cab gives specific colour-light indication in the case of wheel-slip, engine stoppage and boiler failure, in addition to the general fault indicator and fire alarm bell, and a fault panel in the engine compartment identifies the type of failure operating the general fault-indicator light. All indicator lights normally run dim and are brightened on occurrence of a fault.

In addition to providing an indication in the cab as mentioned above, the operation of the wheel-slip relay reduces the tractive effort until the controller is notched back appropriately, and operation of the earth-fault relay removes power from the locomotive as well as causing a fault indication.

CONTROL EQUIPMENT.

A four-motor reverser of new and compact design is incorporated, giving an appreciable saving of space compared with the more usual arrangement of two two-motor reversers, and the conventional battery contactor and reverse-current relay are replaced in the charging circuit by a silicon diode rectifier which blocks reverse currents from the battery. The master-controllers are specially designed to drop into the driver's desk structure in the cab and, as stated earlier, incorporate the engine-speed air-control valves.

The bulk of the control gear is housed in one main control cubicle, mounted in the engine compartment against the bulkhead separating this from the boiler compartment, and adjacent to the main and auxiliary generators. The cubicle is divided into two parts, one accommodating the main power equipment and the other the auxiliary gear, and a very neat layout of components has been achieved. Fault indication lights and certain switches are mounted on the side of the cubicle.

Traction motor field-divert resistors and generator self-field resistors are mounted in the boiler compartment, while the generator separate-field resistors are combined with the servo-regulator in a single unit mounted on the main generator. Mounted in the side of the locomotive, near the control cubicle, is the battery isolator, so arranged that in emergency it can be operated from track level.

ACKNOWLEDGEMENT.

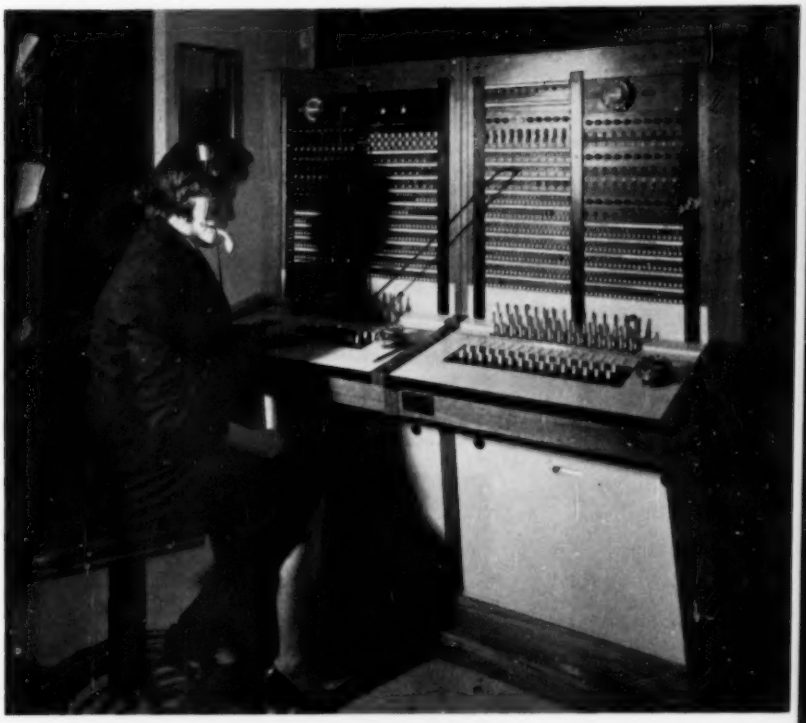
Acknowledgement is due to British Railways and to the Birmingham Railway Carriage and Wagon Co. Ltd. for assistance in preparing this description and the accompanying illustrations.

Electrical Equipment for the 'Canberra'

For the new 45 270 ton P & O Orient liner 'Canberra', G.E.C. has supplied virtually the complete lighting installation, comprising some three miles of cold-cathode tubing, together with hot-cathode tubing and tungsten lamps. The design of the 'Canberra' represents a break with tradition, and the lighting of the main public spaces is equally unconventional in that it can be varied to suit both the purpose of the room and the mood of the occasion.

In addition to the lighting installation, G.E.C. has supplied the telephone system and luminous call and fire alarm services, together with large quantities of cables, motors and control gear.

The tourist dance space is illuminated by Osram tungsten lamps contained in prismatic Perspex 'bricks' to give a sparkle effect. Cold-cathode cornice lighting supplements the main illumination.



The 500-line two-position manual telephone switchboard for passenger services.

One of the wings of the first class dining saloon. The main illumination is provided by cold-cathode tubing recessed into the ceiling; artificial windows lit by cold-cathode tubing mounted behind Perspex screens provide a daylight effect if required.

A Rectifier-controlled Winder

THE winder described in this article is of exceptional interest in that it is the first G.E.C. installation in which the grid-controlled mercury arc rectifier has been used as the basis of a closed-loop control system for a colliery winder drive. The Company has, of course, supplied large numbers of electric winders incorporating closed-loop control to mines in Great Britain and overseas, but these have been either of the d.c. type with Ward Leonard control or of the a.c. type in which the speed of a slipring induction motor is varied by a liquid resistor actuated by automatic control gear.

The capital cost of the rectifier-controlled winder is greater than that of the equivalent a.c. winder, but less than that of the Ward Leonard controlled d.c. winder. The rectifier-controlled winder, however, has the highest efficiency, and although the instantaneous maximum demand is high, there are many duties for which its running costs are lower than those of the other two types. In addition, the rectifier-controlled winder possesses the inherent advantages of extreme manoeuvrability and fast decking times, particularly when several decking levels are used.

The winder, which is shown in fig. 1, is installed at Birch Coppice colliery in the East Midlands Division of the N.C.B.; it is rated at 1490 h.p. and is designed to raise 300 tons of coal per hour from a depth of 1032 ft. The single parallel drum is 18 ft in diameter and is driven through single-reduction helical gearing by a d.c. motor with a speed range of 0/300 rev/min. Two 12-anode grid-controlled mercury arc rectifiers operating from an 11 kV a.c. supply provide the d.c. supply for the winder-motor. This rectifier equipment, together with the winder-motor and the control gear were supplied by G.E.C., while the mechanical parts of the installation were built by Robey & Co. Ltd.

Fig. 1.—1490 h.p. rectifier-controlled winder at Birch Coppice Colliery.

CONTROL SCHEME.

The basic control scheme of the winder is shown in fig. 2. The scheme is essentially one of closed-loop speed control using motor field reversal as a means of regeneration and of reversal of direction of rotation.

The winder-motor speed is measured by means of a tachogenerator and the output of this is compared with a pattern-speed voltage derived from a potentiometer. The resultant error voltage is amplified by a magnetic

amplifier. This amplifier also receives a signal proportional to motor armature current, derived from current transformers in the incoming d.c. line to the rectifier; this signal over-rides the speed signal when the motor armature current exceeds a preset limit. The output of the amplifier feeds the grid-pulse network whose output varies in phase in accordance with the control power fed into it.

Thus the speed of the main motor is controlled by a typical closed-loop speed control system with over-riding current limitation.

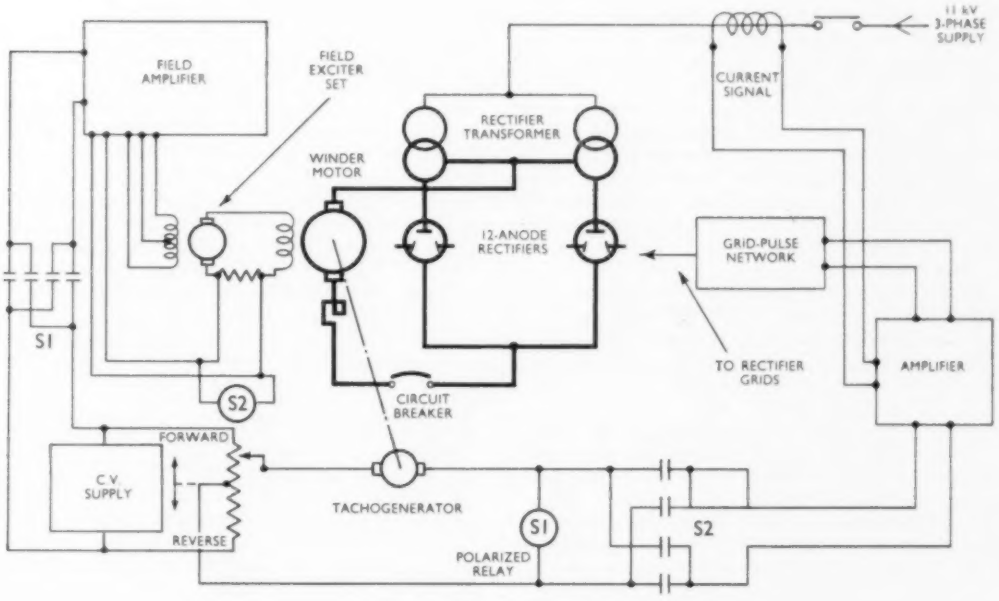


Fig. 2.—Simplified schematic diagram.

In order to provide regeneration and reversal of direction of rotation, the motor field is reversed. This field is supplied from an exciter arranged as a constant-current control system. The ceiling voltage of the exciter is many times the normal field voltage, so that when reversal is called for a high forcing voltage is applied.

The field is reversed by reversing the fixed reference voltage to the field constant-current system. When this is done the field exciter very rapidly produces its ceiling voltage, which is maintained until the field is fully reversed, when the applied field voltage falls automatically to normal value. The field reference voltage is reversed by the relay contacts *S*1. The coil of *S*1 is connected to the error voltage so that the field is reversed whenever the error voltage is reversed. This may happen either as a result of a movement of the controller or as a result of an overhauling load on the winder motor. When the error voltage reverses, the rectifier grid phase is retarded fully and all current is cut off from the motor armature. Simultaneously *S*1 operates and initiates reversal of the motor field.

As soon as the motor field current has passed through zero, polarized relay *S*2, whose coil is operated by the motor field current, changes over. This reverses the error voltage applied to the magnetic amplifier and also to the grid-pulse network. The grid phase now commences to advance and current builds up in the motor armature circuit until the speed loop is again balanced, the current being limited to the preset level if it should tend to rise too high. It will be noted that the current builds up in the armature circuit before full field is reached; thus there is a minimum of dead time and the motor torque builds up smoothly with the increasing field strength.

During all periods of rest the field is removed from the motor, the field reference voltage being open-circuited. This is to avoid the risk of producing a high motor torque should a control fault develop when the winder is at rest. The motor circuit-breaker is not normally opened except when the whole equipment is shut down.

With this system a very accurate and rapid response of speed is obtained, the dead time during field change-over is reduced to a minimum, and moving contacts are reduced to a few low-power, low-voltage relay contacts.

ACKNOWLEDGEMENT.

Acknowledgement is due to the National Coal Board for permission to photograph the installation and to publish this description of it.

Railway Signalling Circuits for a.c. Traction Systems

By H. J. N. RIDDLE, A.M.I.E.E., M.I.R.S.E., S.G.E. Signals Ltd., Wembley.

The modernization of British Railways involves the conversion of existing electrified lines from direct to 50 c/s alternating current traction, together with the installation of new a.c. traction systems. Because of these changes, new signalling systems have been evolved which are immune to interference from traction currents in 50 c/s a.c. systems, and also, in some instances, to interference from d.c. traction systems at the same time.

THE decision by British Railways to employ 50 c/s a.c. for all future extensions to their electrified systems, and to convert very much of the existing d.c. system to a.c., has had a profound effect upon the signalling arrangements. Apart from one or two experimental electrification schemes using a.c. traction (as on the London, Brighton and South Coast Railway for example), d.c. traction was employed for all the electrification schemes over many years, and a great deal of experience and skill in rendering the signalling systems immune to leakages from the powerful traction circuits was achieved. The Underground and Tube Railways played no small part in this, and here, as with the main-line electrifications, one of the simplest and most reliable lines of attack on the problem was to employ alternating currents for signalling purposes, using equipment inherently incapable of responding to d.c. energization, even if it occurred. With the coming of the Grid System and universal availability of 50 c/s power supplies, the remaining difficulties preventing the adoption of these methods disappeared and a highly satisfactory range of equipment was available from the signalling manufacturers to enable complete signalling schemes to be devised and executed with certainty of full attainment of safety and economy in their working.

Then came the announcement of the intention to employ a.c. traction. This meant that the equipment hitherto safe against traction current would no longer be so, that entirely new equipment must be substituted where existing electrifications had to be converted to a.c. traction and that, together with the requirements for new installations, an urgent need faced the signal engineers of British Railways for equipment which would be immune to 50 c/s alternating currents. In many places the situation would arise where the equipment must be immune to both d.c. as well as 50 c/s a.c. interference. The manufacturers of signalling equipment were invited to assist in finding solutions to the problem and initial trials of equipment took place near Fenchurch Street Station in 1956.

This article deals principally with the methods adopted by S.G.E. Signals Limited, but comments where necessary on methods employed by others.

INTERFERENCE FROM TRACTION CURRENTS IN SIGNALLING CIRCUITS.

The ways in which 50 c/s traction current may affect the signalling circuits may be summarized as follows:

(1) By induction into the signalling control cables which run beside the line, the source here being the field surrounding the overhead traction line (catenary) and arising from traction return currents which run partly in the rails, partly

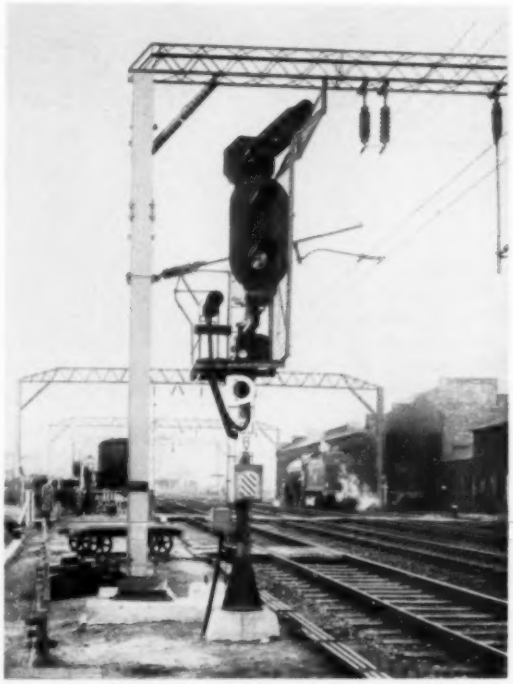


Fig. 1.—S.G.E. signalling equipment on the recently converted Colchester-Clacton line.

through the earth and to a greater extent (in the later traction systems) through a special return conductor.

(2) By accidental contact between the live side of the traction system and some part of the signalling system.

(3) As a result of traction voltage-drop longitudinally along the rail (or rails) carrying the return traction current.

The last case provides by far the greatest problem because in that all-important item of signalling, the track circuit, the rails carry signalling currents as well as the traction current.

THE TRACK CIRCUIT.

The track circuit is an arrangement used for proving that a section of railway line is unoccupied by any vehicle, as a prerequisite of any permission to proceed into the section; permission is indicated to the driver of an approaching train by colour-light or other signal. The track circuit is thus the basis of all modern signalling schemes and is to be found to the extent of several hundreds in any large area of signalling, as at Liverpool Street Station, London, for example.

In its simplest form the track circuit is applied to a given section (the position and length of the section being determined by the rail traffic and signalling requirements) by the insertion of insulated fish-plates at each end of one of the rails, and by ensuring good conductance of all intermediate rail joints by bonding with copper wire. Current applied between the two rails at one end of the section from a feed battery is conducted by the rails to a track relay at the far end. The relay remains energized in this way until the rails are connected together by one or more wheels and axles; the release of the relay denotes that the track is occupied somewhere along its length. Failure of the component—breakage of connexion, exhaustion of the battery, short-circuit or open-circuit of the relay coils, all result in the relay failing to denote 'section occupied'. This constitutes a 'safe-side failure' and is acceptable if it occurs very infrequently.

When the running rails are used for traction return, the uninsulated rail carries this current as well as the signalling current, and if a traction volt-drop of a volt or two occurs over the length of the rail this false energy will be directly applied to the relay when the feed end of the track circuit is occupied. This will result in a relay of the tractive armature type remaining operated, or being re-operated, even though the section is occupied. This would constitute a 'wrong-side failure' and is quite inadmissible. This liability is overcome when d.c. traction is employed by substituting for the feed battery a feed transformer supplying alternating current to feed the track relay through the rails. The a.c. relay is an induction-disc device in which the incoming signalling current energizes a control coil, the consequent alternating flux coupling with eddy currents induced into the disc or vane by a much more powerful local coil obtaining current from a local power source. Unless the signalling currents are identical in frequency and in approximately correct phase-relationship to the local current, the relay remains in the de-energized position. Direct currents in the control coil are completely unable to move the vane whatever their intensity and yet the working of the relay by the a.c. signalling current, with or without a d.c. component in addition, remains quite satisfactory. The relay contacts, being mechanically coupled to the vane, are opened or closed by its movement. Typical a.c.-fed track circuits for use on d.c. traction lines are shown in fig. 2.

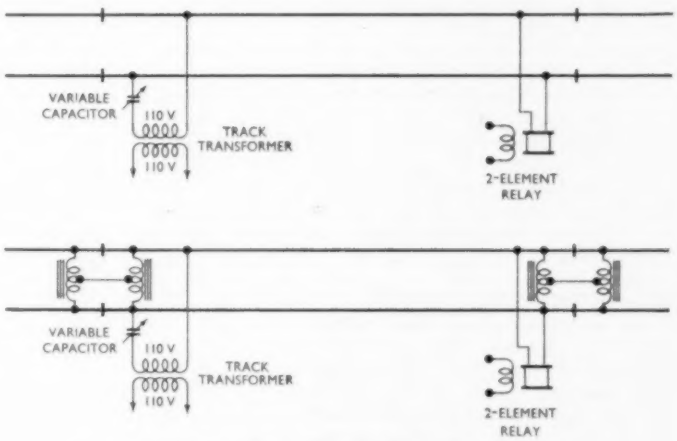


Fig. 2.—Typical a.c.-fed track circuit for use on d.c. traction lines: (above) without, and (below) with, impedance bonds.

SPECIAL TRACK CIRCUITS FOR USE IN 50 c/s TRACTION AREAS.

The voltage-drop arising from the traction current in the common rail is inevitably greater per ampere with a.c. traction than with d.c. This is due to the inherent inductance of an iron rail, and original estimates of possible maximum working values of 15 to 20 volts drop have been adjusted, after experience, to a maximum of 100. However, traction short-circuit conditions are assumed to be capable of giving rise to a volt-drop of 400 volts for a fraction of a second. Since some, or all, of this may be applied directly to the track relay or to the feed-end equipment, very careful consideration had to be given quite beyond the simple requirement of securing operation under normal conditions.

The following list includes some of the methods which have been used or proposed for meeting the

problem which arose when 50 c/s traction was adopted:

(1) Use of alternating current for signalling having a frequency of 83⅓ c/s. Current at this frequency can be produced from 50 c/s supplies by synchronous converters employing motors with six poles, while the generators, directly driven, have ten poles.

(2) Use of signalling frequencies of 75 c/s produced by static conversion from 50 c/s supplies.

(3) Use of higher-frequency current of between 300 and 1000 c/s generated by valve oscillators deriving their energy from the 50 c/s supply. A method originated in France, and extensively used by the French State Railways, it has been tried experimentally in this country with considerable promise.

(4) Use of so-called 'coded track circuits' employing d.c. signalling energy fed to the track in a continuous train of pulses at some 60 to 200 pulses per minute, to hold a relay energized at the far end of the section so long as the pulsed character is sustained. If a steady power (d.c. or a.c.) supplants the pulsed feed, the relay falls.

(5) Use of a d.c. track circuit in those areas where there is no d.c. traction or other source of d.c. leakage.

83⅓ c/s TRACK CIRCUITS.

An example of a track circuit employing the first method is shown diagrammatically in fig. 3. The arrangement is very similar to the simple d.c.-fed track circuit of fig. 2 except for the use of 83⅓ c/s power at the feed, and the inclusion of tuned filter-elements between the rails and the relay. Also the 'local' coil of the relay is fed from a separate 'pure' supply of 83⅓ c/s. This separate supply, which may feed numerous relays, is derived from a winding on the generator having no electrical connexion to a second winding which feeds energy to the rails of this and other track circuits of the same type in the area. The separation of the windings is a precautionary measure and overcomes the possibility of false operation by traction energy which may be conducted from the rails, through the feed transformers, to become effective on the 83⅓ c/s busbars. This could happen because of the finite impedance of the generator output winding and the leads, or in the event of the opening of the connexions to the generator busbars. If, under these circumstances, the same busbars also supplied the relay local coils the relay might conceivably become falsely energized even when the section was occupied by a train.

The two outputs of the special generator must obviously be kept in synchronism, and this is accomplished quite readily by having the rotors for both outputs on a common shaft. As an additional precaution the cables which distribute the 'pure' supply to the relay local coils of all track circuits in an area are carefully screened to avoid inductive pick-up. Furthermore this supply is monitored by an alarm device to give warning if more than a very low 50 c/s component is present on the 83⅓ c/s busbars.

A great many of these track circuits have been installed without difficulty in the course of conversion work on the Eastern Region of British Railways and elsewhere, and operated very satisfactorily while the d.c. traction system was still in use. They continued in this way, without any modification, when the traction system was changed over to 50 c/s a.c.

It is interesting to note that the double-element relay with its basic principle of an induction disc of non-ferrous metal has proved its worth in the new role. It now remains unaffected by 50 c/s current and works only with 83⅓ c/s current, because current of that nature only is supplied to the local element. That it does so respond, even when dissimilar currents are also present in the control coil, mixed with the 83⅓ c/s signalling current, is also an essential requirement, since in normal work under 50 c/s traction the

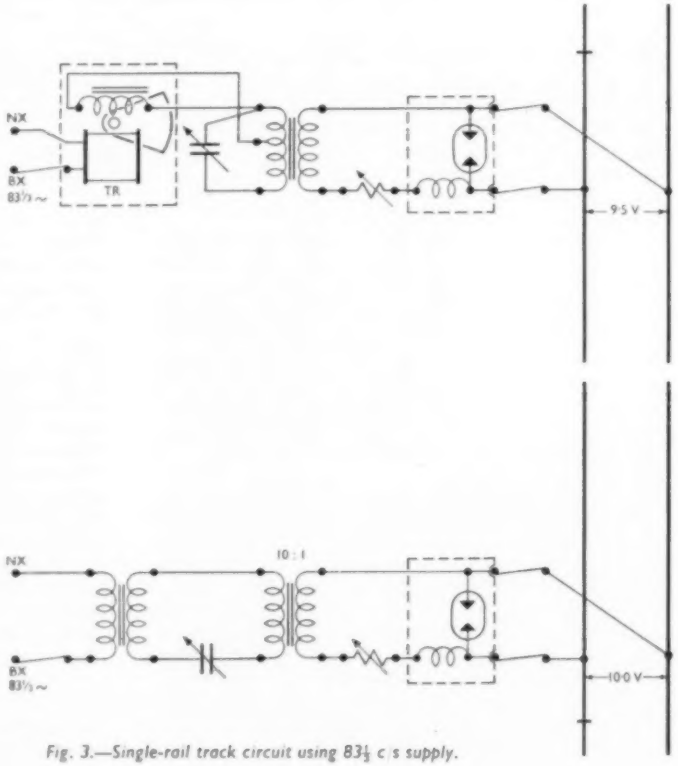


Fig. 3.—Single-rail track circuit using 83⅓ c/s supply.

unwanted 50 c/s component fed to the relay may be much greater in magnitude than the 83⅓ c/s current which continues effectively to keep the relay in the operated condition. When the track circuit is occupied by a train the 83⅓ c/s current is almost completely suppressed, or diverted from the relay, but the 50 c/s current may actually increase. Even so the relay falls. Despite the refusal of the relay to operate with 50 c/s current it is desirable to reduce the level of such power which reaches it otherwise saturation of the magnetic circuits and overheating of the coils may occur. Filter stages are therefore incorporated consisting of a tuned transformer inserted between the rails and relay. Protection against high-voltage surges is given by the addition of a gas-discharge tube at both ends of the track, as shown in fig. 3; any peak above 200-300 volts is diverted and if the high energy level persists the fuses in the track connexions blow. The arrangements shown in fig. 3 and 4 are fully immune to d.c. leakage as well as to 50 c/s leakage.

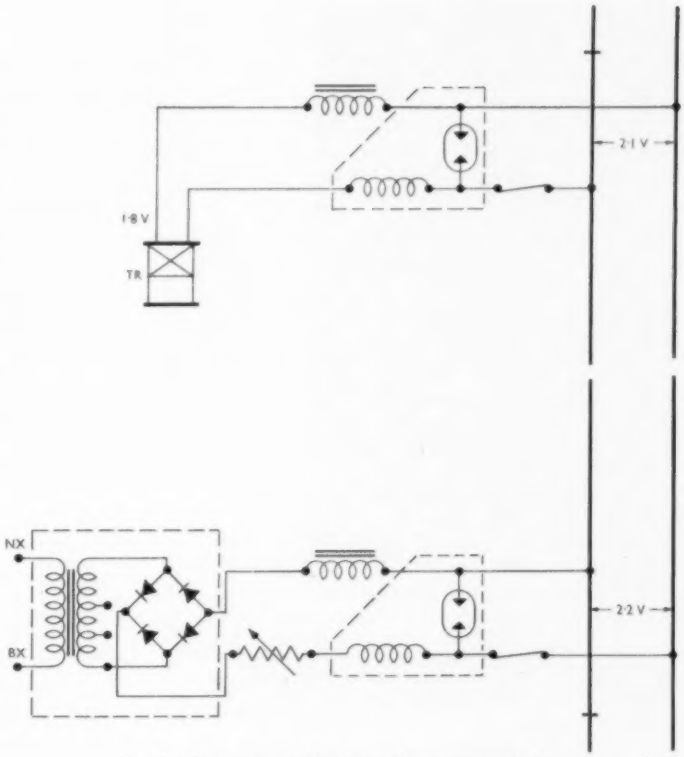


Fig. 5.—Typical d.c. track-circuit with protective chokes.

DOUBLE-RAIL TRACK CIRCUIT, 83⅓ c/s.

Where traction current is so heavy as to require both rails for its return, impedance bonds are added to the arrangements just described, as shown in fig. 4. The fact that the return traction current divides to flow through the two halves of each bond in equal amounts and opposite directions, results in the cancellation of the reactances leaving only the ohmic resistance to traction current. This amounts to about 0·00004 ohm at each bond. Although some 83⅓ c/s signalling current is lost from rail to rail through the two bonds of each track circuit, this is limited by the combined inductance of both halves of the winding in each bond, and the total impedance per bond may be as high as one ohm at 83⅓ c/s. By the inclusion of resonating windings and tuning capacitors, as shown in the diagram, the impedance may be raised to some four ohms.

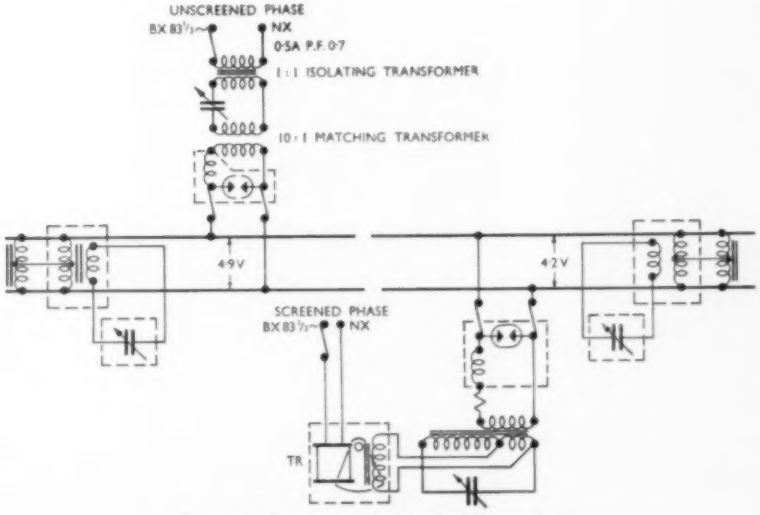


Fig. 4.—83⅓ c/s track circuit with impedance bonds.

At first sight the double-rail track circuit may appear to have advantages beyond the main fact that it can deal with

twice the traction current carried by the single-rail track circuit. However great the voltage drop along each rail, it is the same in both rails, from which it follows that none will be impressed on the track relay when the track is occupied at the feed end (in the manner described for the single-rail track circuit) and the filter network might seem unnecessary. The ideal condition of equal sharing of traction current by both rails is, however, not always attainable, also the risk of a broken connexion between one end of a bond and the rail, with the consequent throwing of the whole traction current into the side which remains connected, cannot be overlooked. In either case the result would be that 50 c/s e.m.f. appears across the rails. The same basic components and connexions are therefore retained for the double-rail circuit as for the single, as shown on the diagram; only the impedance bonds have been added.

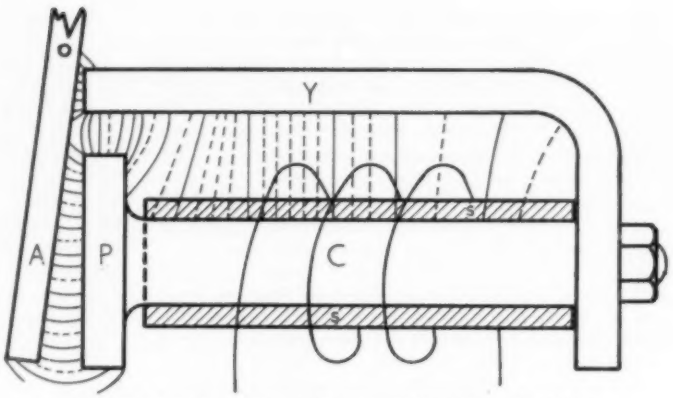


Fig. 7.—Tractive armature electro-magnetic system, slugged to reduce the effect of a.c. on the coil.

A Armature. P Pole Y Yoke
C Core S Slug — D.C. Flux.
--- A.C. Flux

D.C. TRACK CIRCUITS.

The method referred to under item 5 of the foregoing list has been applied extensively on the Eastern Region, the Scottish Region and elsewhere. It is not suitable where adjacent d.c. traction systems exist, or where d.c. leakage from industrial plant is likely to be present.

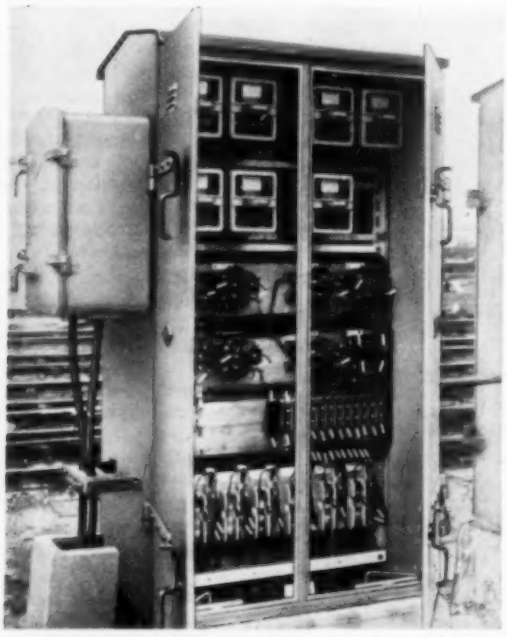


Fig. 6.—D.C. track circuit equipment on the Eastern Region of British Railways.

Immunity of the track relay to alternating voltages two or three hundred times as great as the normal direct voltage at which they operate is achieved either by the insertion of choking coils, or by special design of the relay, or both. Protection has also to be given to the feed equipment and for this the series choke has been widely adopted. Fig. 5 represents a typical track circuit with protective chokes at each end. Fig. 6 is a photograph of apparatus cases on the Eastern Region, housing equipment of this type.

Fig. 7 and 8 show the basic principles employed to render a d.c. relay immune to alternating currents. A normal tractive-armature relay, having the generous proportions for the copper and iron circuits required by railway signalling practice, will require an applied alternating voltage which is perhaps ten times as great as the direct operating voltage before it will be operated, because of the considerable inductance of its windings. The addition of copper slugs between the winding and the cores of the magnetic system increases the alternating voltage which can be tolerated. The immunization can be carried a step further by providing a leakage path for the alternating fluxes which remain after the counter-currents flowing in the slugs have cancelled out the greater part of the magnetizing force. In fig. 8 the effect is carried to the point where saturation of at least some part of the magnetic circuit occurs behind the copper slugs. Relays of this type have been designed and are in production which operate normally on d.c. with about 1 volt, continue to do so with a superimposed alternating voltage of over 100 volts, and yet refuse to operate or remain operated as the alternating component is increased to over 400 volts.

While the relay is thus rendered safe against false operation, it is very desirable to include fuses in the

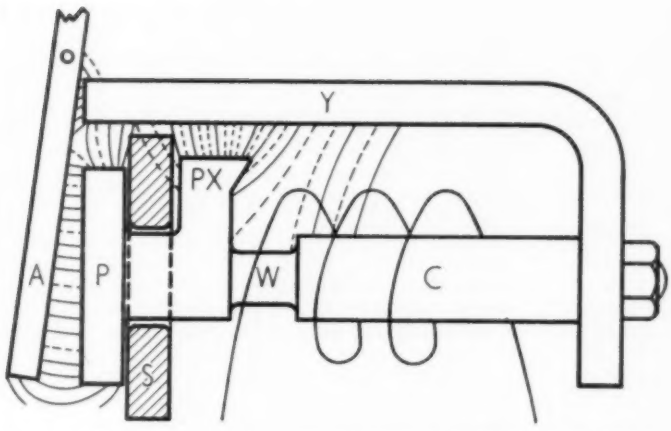


Fig. 8.—Tractive armature electro-magnetic system incapable of operation by a.c.

A	Armature	PX	Pole Extension	Y	Yoke
C	Core	S	Slug	—	D.C. Flux.
P	Pole	W	Waist	- - -	A.C. Flux.

leads from the track so that a prolonged application of these high levels of a.c. (above 100 volts) will not damage the windings. As a further precaution gas-discharge arrestors may be included, as in fig. 3, 4 and 5.

When a relay employing the principles explained by fig. 8 is employed it is obviously unnecessary to include chokes at the relay end of the track, except in sections where the traction voltage-drop is likely to be of a high value for long periods and would otherwise raise the temperature of the relay windings to an undesirable extent.

At the feed end of d.c. track circuits, chokes are included as shown in fig. 5 and are effective in two ways: firstly, to prevent damage to the feed rectifier, and secondly to reduce the d.c. component which would arise from the rectification of any a.c. traction current reaching the rectifier and which would then augment the normal feed current. The necessity to avoid the first trouble is obvious, the need to prevent the second is that the track circuit may be rendered less responsive to the wheels of vehicles which make poor contact with the rails.

The reliability of the whole arrangement may be further increased by the inclusion of two separate chokes in the feed-end circuits so that in the event of one choke becoming ineffective by short-circuit, or other cause, effective protection remains. At least one Region of British Railways demands this additional protection, while dispensing with gas-discharge arrestors.

PROTECTION OF OTHER SIGNALLING EQUIPMENT.

The need for protection of other equipment arises in the main from currents which may be induced into line wires or cables. Fortunately a single cable carrying the go and return lines ensures that both suffer the same induction and no difference of potential will exist between the lines at any one point along its length. Thus the working of a relay connected at one end and a switched supply at the other would not be affected by the induced voltage, but if one line became earthed at one end and the other line became earthed at the other end, the alternating power induced in one line might be supplied to the relay. Fortunately the great majority of line relays used in modern signalling systems have highly self-inductive windings, and being provided with a permanent magnet for obtaining vehicle hold-down characteristics, are virtually polarized and unaffected by the application of a.c. at several hundred volts.

Other equipment employing unpolarized tractive-armature movements—lever locks, banner signals, etc., also have highly inductive windings and are sufficiently immune against false energization, but may require the insertion of a choking coil to reduce the amount of 50 or 100 c/s vibration which is otherwise set up in the movement by induction in the d.c. energized or de-energized condition.

CONCLUSION.

It is gratifying, both to the signalling departments of British Railways and to the manufacturers, to contemplate the successful achievement of so much which appeared formidable, if not impossible, five years ago.

The reliability of signalling systems employing the new techniques is extremely satisfactory and certain fears which had been entertained regarding the extra knowledge required for the maintenance of the additional equipment have proved unfounded.

The execution of these ' conversions ' has brought to S.G.E. Signals Limited (and hence to Union Works and other departments of G.E.C.) a great deal of work, which has required careful planning and timing to coincide with requirements on site. A small example of this was the re-winding and servicing of some hundreds of double-element vane-type d.c. relays, in connexion with the Liverpool Street Station and Fenchurch Street Station areas. These relays, having been operating for several years from 50 c/s signal supplies, had to be rendered suitable for the new frequency of $83\frac{1}{3}$ c/s. For this purpose a float of relays of some six different types was provided and batches of relays were taken out of service (mostly at weekends) despatched to Union Works and, after conversion, re-introduced together with the additional filter-chokes, etc., to form the new signalling circuits in daily traffic use.

Tropospheric Scatter Propagation

By J. B. LOVELL FOOT, A.M.I.E.E., and W. J. LUCAS, M.Sc.,
Hirst Research Centre.

INTRODUCTION.

THE ionosphere, a complex stratified region of ionized gas particles extending from a height of about 25 to 250 miles above the surface of the earth, has played an important part in long-distance radio communications for many years. At frequencies below 30 Mc/s successive reflections of radio waves between the ionosphere and the surface of the earth have enabled radio links to be established over distances of many thousands of miles. At higher frequencies, however, the ionosphere is substantially transparent and until the last decade it was generally held that the only mechanism by which radiation at such frequencies could penetrate consistently beyond the radio horizon was diffraction round the surface of the earth. The troposphere, a region extending from the surface of the earth up to a height of about eight miles had only a minor role to play—that of superimposing small random amplitude fluctuations on an otherwise steady signal.

The problem of diffraction of radio waves round a smooth spherical earth had been solved in 1911 by G. N. Watson, although some twenty years elapsed before the theory was put into a form suitable for numerical computation. This theory predicts a frequency-dependent exponential decrease in signal level beyond the radio horizon which amounts to 1·2dB/mile at 500 Mc/s and 2·4dB/mile at 4000 Mc/s. Acceptance of these predictions implied that the transmission of radio waves in the metric and centimetric ranges to even quite short distances beyond the horizon would require the use of very high power transmitters and extremely large aerial systems. The part to be played by these very high frequencies in the communication field appeared to be restricted to line-of-sight links.

One man stands out in his refusal to accept these limitations. In 1932-3 Marconi carried out a series of experiments at 600 Mc/s, using the yacht 'Elettra' as a receiving terminal. In one experiment with the receiver mounted on the aft end of the boat deck, the ship steamed steadily away from a shore-based transmitter far beyond the radio horizon distance of 27 kilometres. The transmitter had a power output of only 25 watts and the receiver and the transmitter used 2-metre-aperture parabolic aerials. Signals were received feebly out to a distance of about 258 kilometres, more than nine times the horizon distance. Marconi attributed the success of the experiment to some stratification in the lower atmosphere (i.e. troposphere) and in a letter to the Royal Academy of Italy stated that this mechanism together with 'improvements in the apparatus are likely again to revolutionize radio communications'. In retrospect it seems probable that Marconi had demonstrated experimentally the existence of U.H.F. propagation beyond the radio horizon which could not be explained in terms of either diffraction or ionospheric reflection and which today is given the name of tropospheric scatter. However, at that time, the experts in the propagation field held that Marconi's results arose as a consequence of unusual or freak atmospheric conditions which were not likely to occur with sufficient regularity to ensure a reliable method of long-distance communication. If other commitments had not made it impossible for Marconi to continue with these experiments, the present state of knowledge of tropospheric scatter would probably have been reached many years ago.

By the early 1940s the smooth-earth diffraction theory was quite generally accepted and measurements of signal strength just beyond the horizon had produced results in good agreement with predictions. No attempt was made to reproduce Marconi's experiment nor was it considered worthwhile to do so. The start of the second World War and the need for a radar defence system gave a great impetus to the development of high-powered transmitter valves and large aerial systems for waves in the metric and centimetric ranges. With the operation of high-power radar sets came reports, isolated at first, but increasing in number as more and more sets came into use, of radar ranges far exceeding those predicted by the diffraction theory. Eventually the reports became too frequent to ignore and to account for what were still regarded as anomalous results the concept of the atmospheric duct was introduced. This required an inversion layer in the troposphere, i.e. a surface across which the refractive index had a relatively sharp discontinuity. This surface reflected the higher frequencies in a somewhat similar manner to the reflection of frequencies below 30 Mc/s by the ionosphere. As a crude analogy, the combination of the inversion layer and the earth's surface can be thought of as forming the boundaries of a parallel-plate transmission line which guides the waves round the curvature of the earth. The existence of such inversion layers was verified experimentally and the meteorological conditions necessary for their formation determined. It became quite clear that these conditions would not occur regularly enough, nor would they be sufficiently widespread to account for all the reports of long-distance transmission. One

striking consequence of these 'anomalous' transmissions was the suspension in 1949 of television frequency allocations in the United States because of unexpected interference between widely separated television transmitters.

A review of the accumulated experimental data was undertaken in 1950 in America by the Bell Telephone Laboratories, and indicated clearly that the results as a whole could not be explained by any of the existing theories or even any combinations of them. A completely new theoretical approach to the problem seemed to be required. Although most of the data was for frequencies below 100 Mc/s, where it appeared that signals could be received consistently over ranges of 200-300 miles, there were indications that similar properties would extend into the microwave region. The possibility of a large extension in the long-distance communication frequency spectrum led to an experimental programme to investigate the characteristics and reliability of beyond-the-horizon propagation in the frequency range 100-10 000 Mc/s. The rate of accumulation of reliable data was relatively slow and expensive. The propagation tests demanded fairly high-power transmitters, large aerial systems and complex signal-level recording equipment and the nature of the signal made it necessary to extend the tests over a long period—preferably a year or more. Although much of the earlier experimental work was done in the United States, E. C. S. Megaw in this country made some of the first measurements on metric and centimetric waves. During his work at these Laboratories, and after his appointment at the Admiralty in 1946, he conducted a number of experiments concerned mainly with propagation over sea paths of up to 200 miles.

THEORETICAL CONSIDERATIONS.

The possibilities of the new approach to long-distance transmission aroused considerable theoretical interest and, as was inevitable, rather similar ideas occurred to several people in a relatively short time. The first theoretical attacks on the problem were made in the United States by Booker and Gordon and in this country by Megaw. Both theories used the same basic ideas, the difference was only one of approach. The new concepts introduced will be considered briefly and an attempt made to give a simple physical picture of the propagation mechanism envisaged by the theories.

The mean value of the refractive index at radio frequencies at the surface of the earth is greater than unity by about 3 parts in 10^4 and falls to unity at a great height. The rate of decrease is such that a ray which leaves the surface of the earth in a nearly horizontal direction follows, on the average, a curved path which has a constant radius of curvature equal to four times that of the radius of the earth. This leads to a convenient transformation in which nearly horizontal ray paths can be represented by straight lines over an earth with an effective radius equal to 4/3 times the true radius. The radio horizon distance is, therefore, somewhat greater (1·15 times) than the corresponding geometric value. The classical theory postulates that the atmosphere is a completely static system and that this increase in horizon distance is the only effect that the troposphere has on propagation. The new theories retain the idea of a 4/3 earth's radius to account for the average gradient in the refractive index, but point out that the picture of a completely static atmosphere is an extreme idealization. Everyday observations, such as the gustiness of wind and the scintillation of distant lights, point to the fact that the atmosphere is in a state of permanent turbulence and it is the whole essence of the scattering theories to ask what effect the refractive index fluctuations, which must accompany the turbulence, have on a wave passing through it.

The dynamics of turbulence is still poorly understood. However, the general picture presented by the theory in its present state is that large-scale pressure variations, which can be regarded as the source of turbulent energy, establish large eddies in the atmosphere which gradually disintegrate into smaller and smaller units. The transfer of energy through the set of eddy sizes is accompanied by a certain amount of loss and eventually a state is reached when the viscous forces are great enough to inhibit the formation of still smaller eddies. The range of eddy sizes present in the atmosphere is believed to extend from several hundred metres down to about one millimetre. Kolmogoroff has suggested that over the central part of this range the system will be in a state of statistical equilibrium and this hypothesis has enabled dimensional analysis to be used to determine how the turbulent energy is distributed among the various eddy sizes. Fortunately it is just those eddy sizes which are of most importance in the propagation of centimetric and metric waves.

One theory starts by considering a volume of the atmosphere whose linear dimensions are large compared with the largest irregularity and concentrates attention on eddies of a particular size. Within the volume there will be many of these and each one will be represented as a dielectric sphere whose radius is a measure of the size of the eddy and whose refractive index is greater than unity by an amount which measures its turbulent energy. The time-dependent situation is obtained by allowing all the spheres to move about in a random manner. If the total range of eddy sizes is divided into a large number of parts, each subdivision can be represented by a system of spheres of appropriate radius and intensity (i.e. refractive index) and the superposition of these will give the overall picture. This has led to a model of the atmosphere which contains a closely packed set of irregularities of varying size and intensity which move about in a completely random manner.

The effect of a particular irregularity on a plane wave travelling through it is then considered. The deviation of a refractive index Δn from unity will be small—of the order of a few parts in a million—and to be of significance the size of the eddy must be large compared with the wavelength. To a first approximation the plane wave will be unaffected because Δn is so small. This is the assumption made by the classical

theories; scatter theories, on the other hand, use this only as a justification for neglecting interaction between different irregularities. The next approximation yields a slightly disturbed plane wave plus a small but significant amount of power scattered out of the incident beam. The scattering by an irregularity can be described in terms of a polar diagram with a main radiation lobe in the direction of the incident beam and a number of small side lobes, the exact shape being determined by the size of the irregularity relative to the wavelength.

The next and final step in the argument is to sum the power scattered in a given direction by all the irregularities within some relevant volume. For example, in the case of a point-to-point link using high-gain aerials this will be the volume common to the main lobes of the transmitter and receiver beams. The random motions of the irregularities result in small Doppler frequency shifts so that the energy scattered in a given direction will not be monochromatic but will be spread over a band of frequencies determined by the velocity distribution of the scatterers. Over a long period there is no net interaction between component waves at the different frequencies; the total mean power scattered in a given direction is therefore equal to the sum of the mean powers scattered by the individual irregularities. The signal received by such a scattering process is characterized by rapid fluctuations over a large range.

The outline given above describes very briefly the method of analysis used by Megaw. Other theories have been based on the idea of a non-turbulent but stratified troposphere which tapers to a vacuum at a great height, but at the time of writing scattering due to atmospheric turbulence has been widely accepted. Recently at an U.R.S.I. conference at Boulder, Colorado, a new theory of over-the-horizon propagation was advanced by K. Bullington based on the coherent reflection of energy from the height gradient of the radio refractive index, the atmospheric turbulence introducing fading but not adding significantly to the average signal level. The full text of Bullington's paper is not yet readily available in this country and it is not yet clear whether the theory will offer a more complete explanation of the many experimental results.

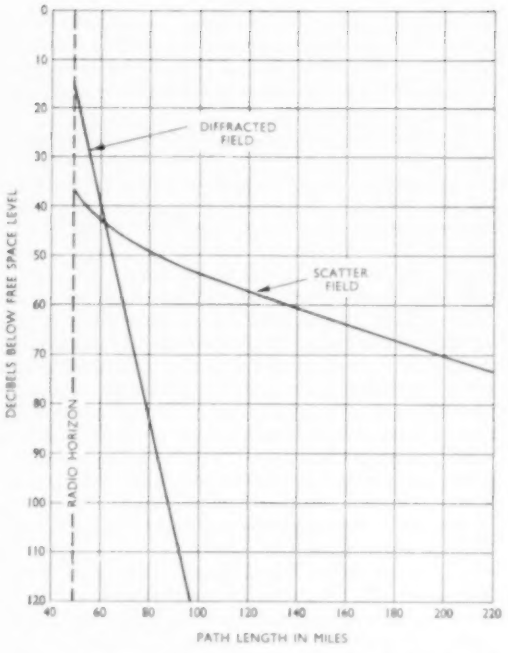


Fig. 2.—Calculated diffraction and scatter field beyond the radio horizon for a typical link.

The basic geometry of a scatter link is indicated in fig. 1; for typical links the path length, d, is in the range 100-300 miles and the scatter angle $\theta \simeq \frac{d}{2a}$ where a is the effective radius of the earth (about 5280 miles), is usually between 1° and 3°. Fig. 2 shows the computed values of the diffracted and average scatter signals as a function of path length for a 3480 Mc/s system with transmitter and receiver aerial heights of 420 ft and 190 ft respectively. It is assumed that the profile of the path can be represented reasonably well by a smooth earth. Immediately over the horizon the dominating propagation mechanism is diffraction and the signal decreases rapidly at 2·2dB/mile. At a point about thirteen miles beyond this the two components become comparable and the subsequent rate of decrease in magnitude of the scatter signal is considerably less than that of the diffracted signal; well beyond the horizon the scattering process is overwhelmingly predominant. The value of $d = 173$ miles, corresponds approximately to one of the experimental links established by the G.E.C., and at

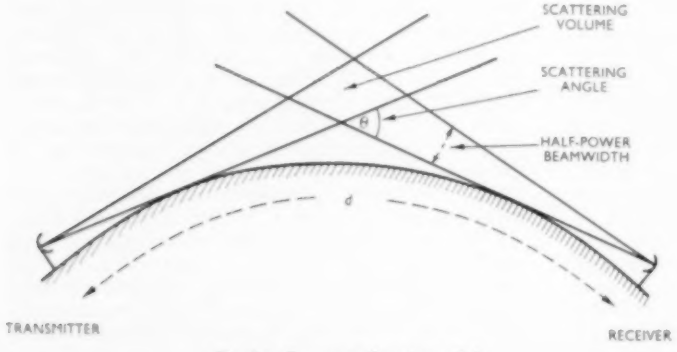


Fig. 1.—Geometry of a scatter link.

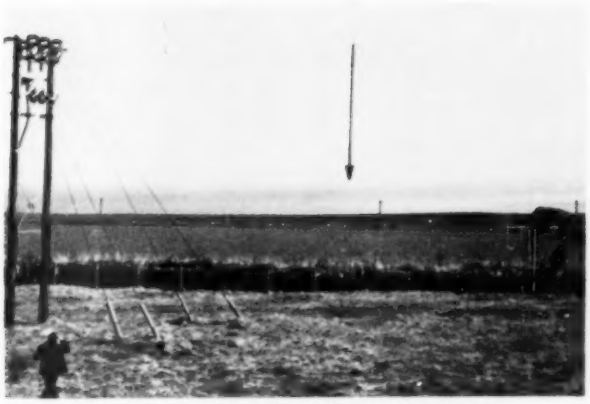


Fig. 3.—View along the transmission path from Start Point.

this distance the scatter signal is 192dB greater than the diffracted field.

The scatter theory, therefore, offers a possible explanation of the many unexpectedly long distance transmissions observed over a period of years. It must be emphasized that the signals, although large compared with those arising from diffraction round the surface of the earth, are still relatively small compared with the free-space signal and to make reliable use of the mechanism high-power transmitters, large aerial systems and sensitive receivers are required. Furthermore, by its very nature, the average signal level would be expected to be very dependent on geographical location and meteorological conditions, while the instantaneous value, since it is the sum of a large number of phase-independent components, would be expected to vary quite rapidly and in a random manner. A detailed prediction of the way in which the average level varies with time can hardly be expected since this would require an accurate knowledge of the atmospheric conditions existing throughout a large volume. Making plausible assumptions, based for example on airborne refractometer measurements, about the values of various atmospheric parameters the average signal level for a particular link can usually be predicted to $\pm$6dB. As a percentage of the total transmission loss (the ratio of the power transmitted to that received expressed in decibels), this usually represents a relatively small error, but practically it is of extreme importance since it may, for example, mean the difference between the use of 10 ft and 20 ft diameter paraboloid aerials. From an engineering point of view, therefore, there is a need for the accumulation of a large amount of data from experimental links. The measurements should be extended over long periods so that both the instantaneous and long-term fluctuations in signal level can be characterized, at least statistically.

PROGRAMME OF INVESTIGATION.

In 1955 the G.E.C. was given research contracts by both the Ministry of Supply and the Admiralty for an experimental study of tropospheric scatter propagation in the range 3-10 kMc/s. At this time there was a paucity of practical information for this frequency range. The primary object of the programme was a long-term investigation of the characteristics of an unmodulated scatter signal. A link, operating at 3480 Mc/s over a 173-mile path was put into operation in May 1956. The transmitter equipment, using a 500 watt C.W. magnetron, was housed in a trailer with an 8 ft paraboloid aerial mounted on the roof. The unit was located at Start Point, Devon, at a distance of about 500 yards from the edge of a 412 ft cliff and with a clear view out across Lyme Bay. Apart from periodic inspections the transmitter was designed to operate unattended. A photograph of the site is shown in fig. 3. The receiver and signal-level recording equipment was installed at Wembley, the aerial, again an 8 ft paraboloid, being mounted near the top of the 200 ft tower in the Laboratory grounds. A photograph looking along the propagation path from the top of the tower is shown in fig. 4. For a standard radio atmosphere (i.e. a 4/3 effective earth's radius) the transmitter and receiver horizon distances were respectively fifty-seven and seventeen miles, while the angle θ in the great circle plane between the horizon rays, usually referred to as the angular path distance, was 26·5

Fig. 4.—View along the transmission path from Wembley.

milliradians or about 1·5°. In the absence of any special conditions, such as ducting, the signal should, therefore, be predominantly of the scatter type. This particular link was kept in existence throughout the whole of a three-year programme.

A second identical receiving station for the 3480 Mc/s transmissions was set up at Witnesham, Suffolk, for a nine-month period from September 1957 to June 1958. Witnesham lies on the extension of the line through Start Point and Wembley and is 247 miles from the transmitter at Start Point; the horizon distance at Witnesham was 9·5 miles and the angular path distance for this link 41·4 milliradians or about 2·4°. Signals were recorded simultaneously at the two sites and an estimate made of the average attenuation rate with distance at the particular frequency.

The transmissions from Start Point were later monitored at Ditton Park by the Radio Research Station of the D.S.I.R. as a part of a programme to study tropospheric propagation. Ditton Park is situated near Slough at a distance of thirteen miles from Wembley and is only slightly off the path from Start Point to Wembley. Apart from aerial sizes, the receiving equipment at Slough was identical to that used at Wembley and Witnesham. Information has been exchanged with the D.S.I.R. and in particular a comparison extending over several months has been made of the average signal level received at Wembley and Slough.

In addition to the work on 3480 Mc/s, a second propagation link operating at 9640 Mc/s was established in June 1958 over the same propagation path between Start Point and Wembley. The only suitable transmitter available at this frequency was a pulsed radar set with a pulse length of 2 microseconds, a pulse repetition rate of 500 p.p.s. and a peak output of 180 kW. The transmitter was also housed in a trailer and located at Start Point alongside the 3480 Mc/s unit, while the receiver was mounted at the Wembley tower site. Paraboloids of 8 ft diameter were used at both terminals. The output of the video amplifier of the 9640 Mc/s receiver was fed into a pulse-stretching circuit which converted the pulses into a varying direct current whose amplitude followed that of the successively arriving pulses and which had a mean output large enough to operate a conventional pen recorder. As will be seen from the results quoted later, the pulse repetition rate was large enough compared with the average fluctuation rate of the signal to make the output from the pulse-stretcher portray fairly closely the variations in signal amplitude which would have been obtained under C.W. conditions. The two links were operated simultaneously over a period of a year to obtain a direct comparison of tropospheric signals transmitted over the same path at widely differing frequencies. The locations of the various terminals are shown in the map (fig. 5).

SIGNAL ANALYSIS.

The methods of recording the signal level were:

(*a*) Pen recorders in which the varying signal was traced on a paper chart. Two types of recorder were used. One had a paper speed of 3 in. or 12 in./hour and a time constant of about 1 second and the other had relatively high paper speeds of up to 4 in./sec and gave a level frequency response up to 60 c/s. The former was kept in continuous operation during signal transmissions and besides providing a record of the average signal-level variations gave a convenient check that the system was operating correctly. The latter was used only for short periods to examine the fine structure of the signal-level variations.

(*b*) A signal sampling process which recorded the signal-level distribution on counters over any desired period. The sampling rate was about 1 per second and the sampling period very small compared with the average fade duration. Each of ten counters was associated with one of ten standard voltages against which the sample was compared. At Wembley all three instruments were avilable for the 3480 Mc/s signal but only the pen recorders for 9640 Mc/s; at Witnesham only a low-speed pen recorder was used.

The links were operated for at least one or two days during each week and occasionally signal levels were recorded continuously for periods of up to ten days.

Fig. 5.—Map of the propagation path.
(Scale: 1 in. = 105 miles approx.)

In this way a representative picture of the propagation conditions throughout the year and under a wide variety of meteorological conditions was obtained.

The characteristics of a typical tropospheric scatter signal are illustrated in fig. 6; this shows a low-speed chart of the 3480 Mc/s signal-level over a period of several hours. The instantaneous level fades rapidly over a wide range while the mean value changes relatively slowly, reflecting the changing meteorological conditions in the atmosphere. There are two main problems in the measurement of such signals; first, the determination of the long-term variations in average level and secondly a statistical characterization of the amplitude of the signal over a relatively short period in which the average level can be regarded as approximately constant. The two aspects of the problem will be considered separately and illustrated by results obtained from measurements on the links. The results quoted are typical of paths which lie mainly overland.

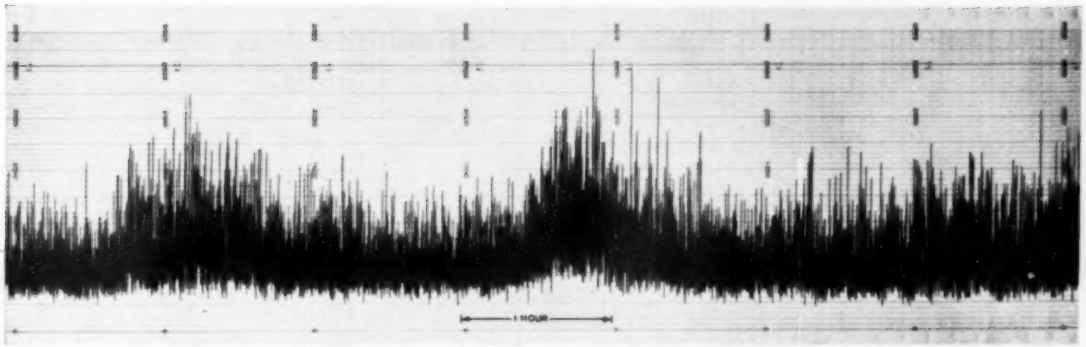


Fig. 6.—Low-speed pen recording of the 3480 Mc/s signal showing normal median level variations.

It has become customary to measure the average level of a signal in terms of the median value of the system transmission loss (the difference in power levels at the aerial feeds of the transmitter and receiver aerials, expressed in decibels), over the period of a half or one hour. For engineering purposes this is the quantity of most interest but from the point of view of the theoretical interpretation of results it has the disadvantage of depending on effects associated with the particular aerial system used and these cannot easily be separated from the purely propagational effects. Because scattering takes place throughout an extended volume of the atmosphere, the energy arriving at the receiver is spread over a range of angles of arrival. The consequence of this is that a narrow beam aerial fails to realize its full-plane wave gain. This is known as the aerial-to-medium coupling loss and is defined quantitatively as the number of decibels the effective sum of the gains of the transmitter and receiving aerials falls short of the sum of their plane wave gains. The coupling loss becomes more serious as the aerial gain increases and sets a practical limit to the size of aerials that it is worthwhile using in a system. At present there appears to be no completely satisfactory way of calculating this effect, nor is its experimental determination easy. For the present systems the coupling loss is thought to be about 3dB at 3480 Mc/s and 8dB at 9640 Mc/s. However, since the two links use aerials of the same size a direct comparison of the system transmission losses will indicate whether for systems of comparable physical size, one frequency has a decisive advantage over the other.

MEASUREMENTS AT 3480 Mc/s.

The measurements for the Start Point—Wembley link will be discussed to bring out the main feature of the median level variability. The hourly medians were found to spread over a wide range of values—typically about 60dB in the course of a year. When the propagation was of the scatter type the hour-to-hour variations were of the order of 1-2dB but exceptional conditions, presumably those associated with some form of ducting, occasionally occurred which resulted in quite sudden increases in signal level of up to 30dB. These high signals usually persisted from 1-12 hours before returning to the original level. At the other extreme very stable conditions sometimes arose in which the median level remained almost constant for many hours. Typical and exceptional types of variation over twenty-four hours are illustrated in fig. 7. The average variation within twenty-four hours for all periods was about 13dB. The scatter-type signal

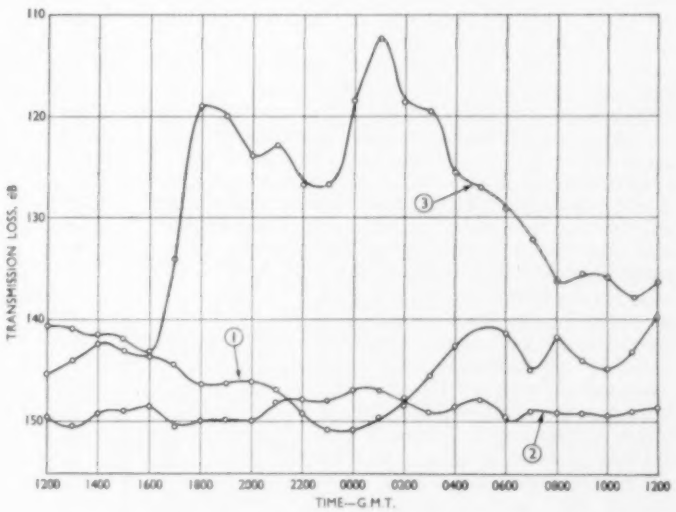


Fig. 7.—Variation of the median transmission loss during a day.
Curve 1.—Average diurnal variation.
Curve 2.—Small diurnal variation.
Curve 3.—Exceptionally large diurnal variation.

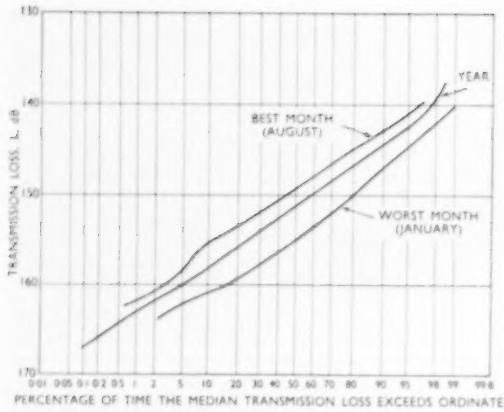

YEAR
BEST MONTH (AUGUST)
WORST MONTH (JANUARY)
TRANSMISSION LOSS, L dB
PERCENTAGE OF TIME THE MEDIAN TRANSMISSION LOSS EXCEEDS ORDINATE

Fig. 8.—Distribution of the 3480 Mc/s hourly median transmission loss for 1958.

showed no systematic variations with the time of day. The ducted signals on the other hand occurred far more frequently in the few hours either side of midnight and in addition showed a definite seasonal dependence, appearing more frequently in the summer and autumn and only very rarely in the winter. However, ducting accounted for about only 2% of the total operating time of the link.

A convenient description of the random variations in the median transmission loss is given by the statistical distribution of the hourly median values. Over the period of a month or longer this can usually be represented reasonably well by a Gaussian Law. Cumulative distributions, plotted on arithmetic probability paper, for the best and worst months of 1958 and for the whole year are shown in fig. 8. Any straight line drawn on such paper corresponds to a Gaussian distribution with a standard deviation given by half the difference between the 16% and 84% levels, and the distribution is completely specified once the mean value and standard deviation are known. Thus although it is impossible to predict the variation as a function of time, a knowledge of this distribution enables the proportion of time that the median signal spends below any selected level to be easily computed. This is clearly of great importance in estimating the reliability of a particular link. The yearly median value for the 3480 Mc/s link is seen to be 152dB (about 70dB greater than the free-space loss) and the standard deviation approximately 5dB, the measurement error is about ±1dB. Assuming an aerial coupling loss of 3dB, a formula due to Norton, Vogler and Rice gives an estimated value for the transmission loss of 153dB. The formula was based originally on a model of the scattering process due to Weisskopf and Villars and later adjusted to give the best fit to a large amount of experimental data obtained in the U.S.A. at frequencies up to 1000 Mc/s. The root-mean-square deviation of the measured data from the derived curve was about 6dB. Taking into account that, in addition, the aerial coupling loss is known only to about ±1dB, the close agreement between the measured and estimated values may be regarded as fortuitous. The monthly median values of the system transmission loss for the period May 1956 to Dec 1958 are shown in fig. 9. A seasonal trend in the curves is evident, the signal on the whole being higher from May to October than in the rest of the year. The loss is greatest in January and February and the difference in level between these and the summer months is, on the average, about 7-8dB.

At Witnesham the picture of signal variability was substantially as described above. The measured yearly median value of the system transmission loss was in this case 161dB while the estimated value was 5dB greater. This emphasizes the fact that at present the predictions are not all that could be desired from the point of view of engineering a proposed link. However, the main object in establishing the second receiver site at Witnesham was to compare median signal-levels received simultaneously at two sites separated by a fairly large distance—in this case seventy-four miles—under as many conditions as possible and to study the difference in levels between the two signals. Fig. 10 shows the median-level variations at Wembley and Witnesham for a period of four days' continuous recording in November 1957. The relative behaviour of the signals at the two sites was the more usual type observed: on the whole the trends in the two signals were similar but there was little correlation between the detailed fluctuations. On occasions, however, the Witnesham signal was equal to or even higher than that at Wembley, while at other times it was as much as 30dB lower. This is illustrated in fig. 11 by a histogram of the difference between the half-hourly medians at Wembley and Witnesham; the differences range from the Witnesham signal being 7dB above to 33dB below that at Wembley. The distribution of this difference is approximately Gaussian with a mean value of 11·7dB and a standard deviation of 5·8dB. This corresponds to an average attenuation rate of the 3480 Mc/s scatter signal of about 0·1dB/mile, a factor of fourteen less than that of the diffracted field.

It is worthwhile mentioning very briefly the

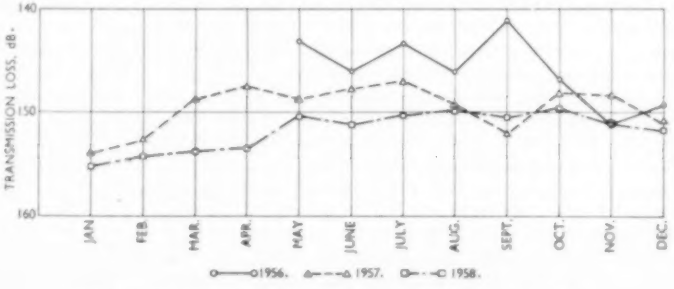
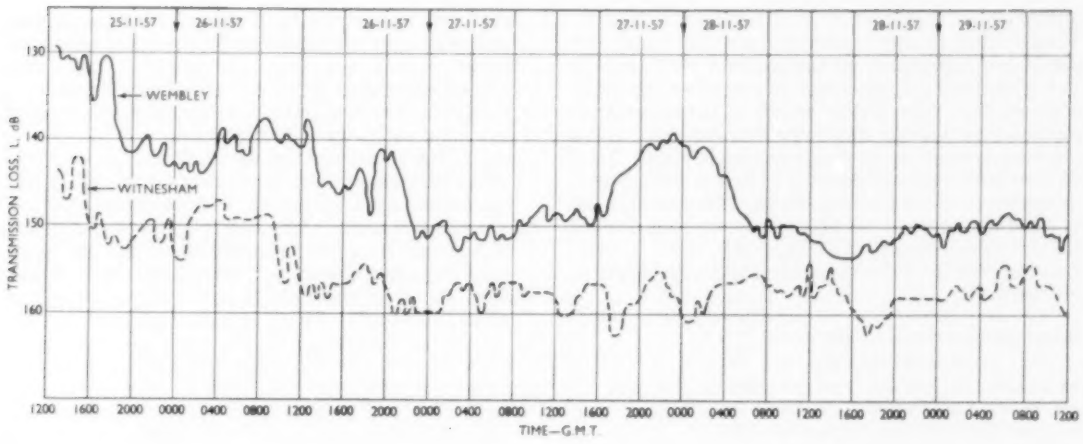
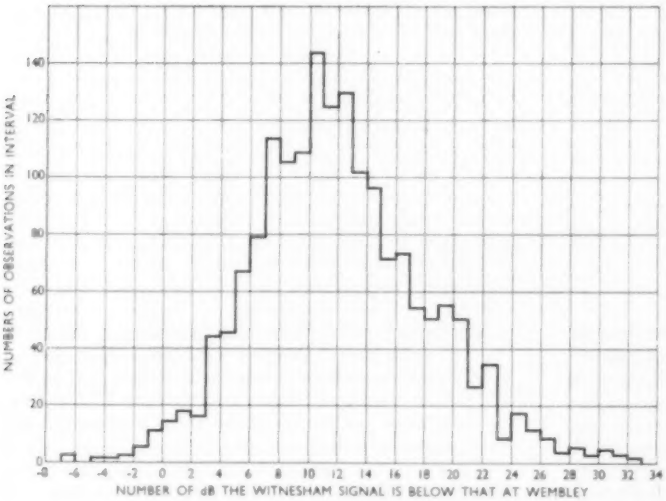


Fig. 9.—Monthly median values of the 3480 Mc/s transmission loss.

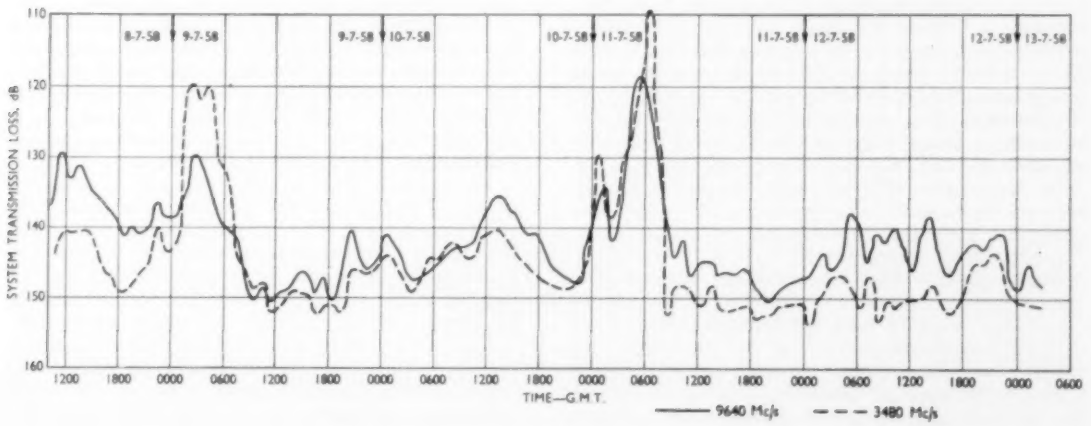


(Above) Fig. 10.—Comparison of the median transmission loss at Wembley and Witnesham during four days recording in November 1957.


NUMBERS OF OBSERVATIONS IN INTERVAL
0 20 40 60 80 100 120 140
-8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
NUMBER OF dB THE WITNESHAM SIGNAL IS BELOW THAT AT WEMBLEY

(Left) Fig. 11.—Histogram of the median level difference between the Wembley and Witnesham signals.

(Below) Fig. 12.—Comparison of the median transmission loss at 3480 and 9640 Mc/s at Wembley for four days during July 1958.



comparison of signal levels at Wembley and Slough. Simultaneous records covering about 250 hours and spread over a period of six months were examined. It should be borne in mind that the effective scattering volumes were quite closely spaced in the atmosphere and it is perhaps not surprising that the signal levels followed one another quite closely even in detail. Thus while at sites separated by seventy-four miles it is only the general trends which are similar, at distances of the order of ten miles, providing the sites are such that the angular-path distances are comparable, there is quite a strong correlation between the detailed variations in median level.

MEASUREMENTS AT 9640 Mc/s.

The short-term picture of the variations in median level at 9640 Mc/s was substantially the same as that at 3480 Mc/s, a typical diurnal variation in the absence of ducting being 14dB with no indication of a systematic dependence on the time of day. Ducted signals were again observed and it is an interesting fact that on the eight occasions during the year that ducting occurred at 9640 Mc/s, similar signals were also present at the lower frequency. The times at which these large signals occurred and their duration were almost identical at the two frequencies, although the increase in level was usually 5-12dB greater at 3480 Mc/s. A plot of the measured values of the hourly median transmission loss at the two frequencies for four days continuous recording, which included two periods of ducting, is shown in fig. 12. The similarity of the variations over a few days was typical of most of the results. The one essential difference is brought out by fig. 13 which shows a plot of the monthly median values of transmission loss at the two frequencies over a period of a year. It is seen that the seasonal dependence is far more marked at the higher frequency. The range of monthly medians is 17dB at 9640 Mc/s compared with 7dB at 3480 Mc/s, the 9640 Mc/s transmission loss being a few decibels less than that at 3480 Mc/s during the summer, but on the average about 5dB greater during the winter months. At 9640 Mc/s, the Gaussian distribution of hourly medians for the year had a mean value of 153dB and a standard deviation of 7·5dB; the latter figure compares with the 3480 Mc/s value of 5·5dB and reflects the greater seasonal dependence. On the whole, one would conclude that the lower frequency link has an advantage but this is by no means decisive.

Many attempts have been made to correlate the hour-to-hour variations in median level with meteorological data; none of these has been successful. The difficulty presumably lies in the fact that soundings taken at a particular point in space cannot hope to represent the detailed conditions existing throughout the relatively large volume of the atmosphere responsible for the scattering process. Certain general tendencies have been noted and these are summarized below:

(*a*) The signal is enhanced during foggy weather.
(*b*) The variation in level is considerably reduced when fog covers the path.
(*c*) Heavy rain over the path reduced the signals at both frequencies, the decrease being far greater than would be expected from the attenuation due to rain alone. This does not appear to be true, however, at all frequencies; at 900 Mc/s, for example, there have been reports of signal enhancement during rain.

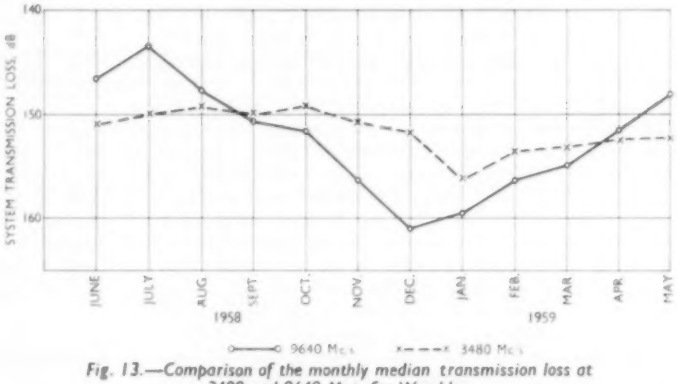


Fig. 13.—Comparison of the monthly median transmission loss at 3480 and 9640 Mc/s for Wembley.

(*d*) During anticyclonic conditions the signal is usually below average for the time of the year.
(*e*) In the presence of warm or cold fronts across the path the signal level tended to be higher than average for the time of the year and the diurnal variations somewhat larger.
(*f*) The only really successful correlation on a quantitative basis that has been reported is between the daily averages of the transmission loss and surface refractivity evaluated at the centre of the propagation path. The surface refractivity is proportional to the deviation of the refractive index from unity and varies mainly as a function of humidity. Correlation coefficients between 0·6 and 0·7 have been observed.

RAPID AMPLITUDE FLUCTUATIONS.

The rapid amplitude fluctuations over a period in which the average level does not change very much will now be considered. The physical picture of the scattering process has suggested that the received signal will be noise-like in character and spread over a band of frequencies, determined by the velocity distribution of the atmospheric irregularities. The application of such a signal to a linear detector will produce a randomly fluctuating d.c. output as indicated by the sample of a high-speed pen recording shown in fig. 14. Although the precise way in which the detected signal varies with

time cannot be predicted, it is possible to estimate the proportion of time spent within any selected limits. In other words the amplitude has known statistical properties which can be described mathematically by the Rayleigh distribution function. For the 3480 Mc/s signal at Wembley the readings of the ten counters in the signal-sampling machine gave the measured amplitude distribution of the detected signal over a range of 27dB.

A considerable amount of work has been undertaken on the problem of amplitude distributions both in this country and in the United States. Since all the reports show a large measure of agreement, it will be convenient to consider the results obtained for the 3480 Mc/s Start Point to Wembley link. The basic period of analysis was usually one hour although shorter periods down to a few minutes have been used on occasions. The majority of the measured distributions confirmed the presence of a Rayleigh distributed component. Frequently, however, there was in addition a steady signal, the amplitude of which varied with meteorological conditions. The distributions for pure Rayleigh signal (i.e. pure scattering) and for the case when there is, in addition to the Rayleigh component, a steady signal whose power is 4dB greater than the mean power of the Rayleigh component, are shown in fig. 15, both curves being referred to their respective median values. The experimental results usually lie between these two. When the median level is low it is found that the amplitude of the signal can usually be described fairly accurately by the Rayleigh distribution function, and since in estimating the reliability of a particular system the lower median levels are of particular importance, this distribution is almost invariably assumed. A combination of this with the Gaussian distribution of the hourly medians provides an overall statistical picture of signal fluctuations.

It was noticed that the very high ducted signals have a somewhat different character. The fluctuation rate is very much slower than that of the typical scatter signal and the depth of fading greater. The amplitude distribution in this case can often be better described by the combination of a small number of signals of constant amplitude but of random relative phase. Physically this could correspond to two or more well-defined discontinuity layers in the atmosphere giving rise to something like specular reflections. However, since such signals are present for only a small proportion of the time, at least on overland paths, and correspond to a substantial increase in median level which more than compensates for the increase in depth of fading, this type of distribution is usually neglected in considering system reliability.

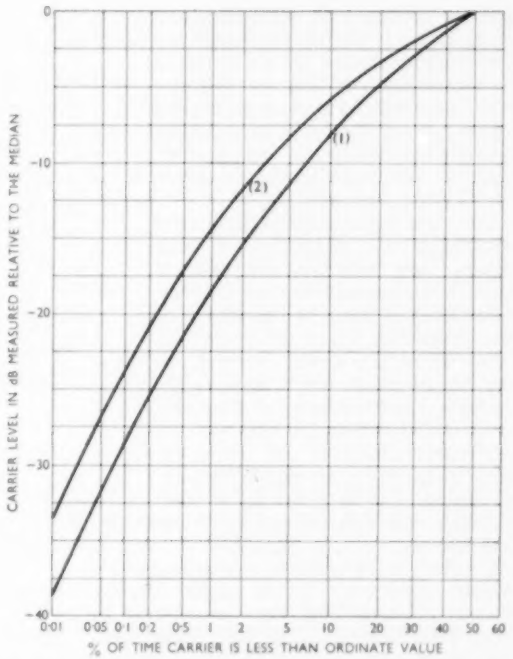


Fig. 15.—Distribution of the instantaneous amplitude of the detected carrier: (1) Rayleigh Curve, (2) Rayleigh plus constant vector. (Constant signal 4dB greater than Rayleigh.)

DIVERSITY.

The fluctuating nature of the signal is clearly a very undesirable feature of this type of propagation. However, by its very nature it provides a means by which the effect of the fluctuations can be minimized. A consequence of the scattering process is that it is not difficult to receive carriers whose amplitude variations lack coherence. For example, at frequencies in the centimetric range, two aerials separated either horizontally or vertically by only a few metres will receive signals from the same transmitter whose amplitudes vary in an almost completely independent manner. The same is true of two carriers separated by a few tens of megacycles and transmitted over exactly the same path. The simplest technique to reduce the effect of fading is to receive two such independent signals, compare the detected amplitudes continuously and select at any instant the larger. This technique is known as either

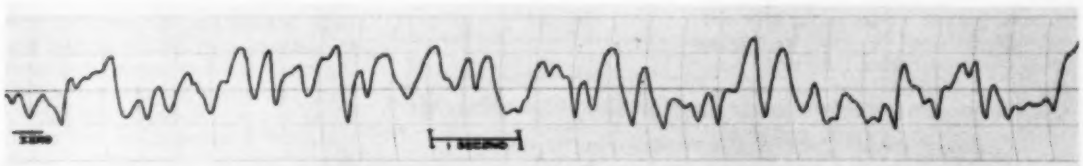


Fig. 14.—Sample of a high-speed pen recording of the 3480 Mc/s scatter signal.

space or frequency diversity reception depending on whether the signals are derived from spaced aerials or from the transmission of different frequencies. Combinations of these can clearly lead to a larger number of substantially independent signals at the receiver terminal; the use of quadruple diversity is quite common.

For two completely independent amplitudes the probability of both signals (and therefore the selected signal) being simultaneously below a given level is equal to the square of the probability of one of the signals being below that level. However, in the case of double space diversity for example, it may happen that the maximum aerial separation that can be conveniently achieved still leaves the amplitudes of the two signals partially correlated. It is, therefore, of considerable practical importance to know the diversity improvement as a function of the correlation coefficient, ρ, between the signal amplitudes. The output distribution of a double-diversity selector system assuming both input amplitudes to be Rayleigh distributed and of the same mean power is shown for various values of ρ in fig. 16. The carrier level is measured in decibels relative to the median value for a single path. A value $\rho=0$ implies completely independent carriers and $\rho=1$ completely correlated carriers; thus the curve for $\rho=1$ is the amplitude distribution for a single channel. The diversity improvement is seen to be a function of level; at the median level the maximum is only 2·6dB while at the 1·0% level (the level below which the signal falls for 1·0% of the time) the improvement is 10.3dB. The important point to notice is that providing ρ is less than 0·5, the diversity improvement does not fall very far short of the optimum and in practice, in the centimetric regions, paraboloids placed quite close together will usually give a worthwhile improvement. Signal selection is not the only diversity technique nor is it the most efficient. The optimum method involves the linear addition of the two signals weighted according to their instantaneous signal-to-noise ratios. The optimum combiner has an advantage over the selector diversity system of about 1·5dB at all levels.

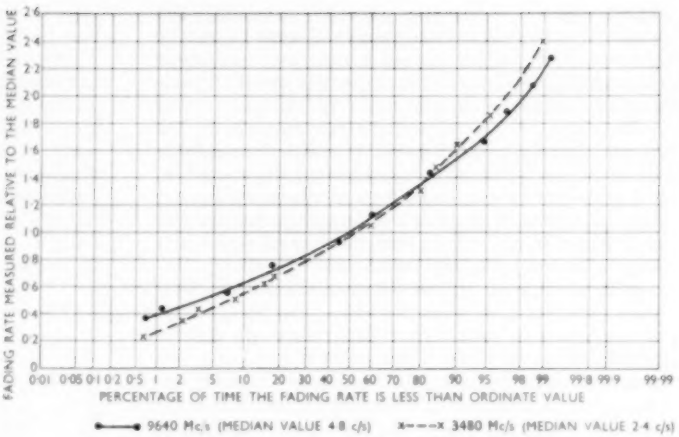
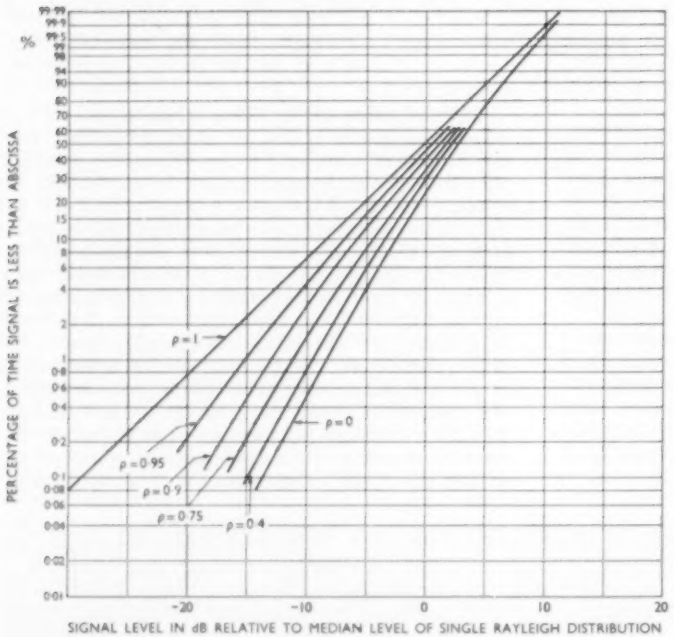

FADING RATE MEASURED RELATIVE TO THE MEDIAN VALUE
PERCENTAGE OF TIME THE FADING RATE IS LESS THAN ORDINATE VALUE
9640 Mc/s (MEDIAN VALUE 4·8 c/s)
3480 Mc/s (MEDIAN VALUE 2·4 c/s)

Fig. 17.—Normalized cumulative distribution plot of the fading rate measurements at 3480 and 9640 Mc/s.



ρ = CORRELATION COEFFICIENT BETWEEN SIGNALS ON TWO CHANNELS

Fig. 16.—Variation of the amplitude distribution of a double-diversity signal with correlation coefficient.

FADING RATE.

The type of measurement so far described specify the time structure of the signal only in a general way; the Rayleigh distribution, for example, gives the proportion of time in an hour that the signal is below any selected level. Some measure of the rate at which the signal fluctuates is clearly desirable. A complete description of the fading would require a knowledge of the Doppler frequency - shift spectrum

resulting from the random motions of the scatterers, but as a useful general parameter characterizing the fading it has become customary to define the average fading rate as the number of times per second the envelope of the received signal crosses the median level with a positive slope. This quantity can be easily determined by a direct count of the median level crossings from a high-speed record of the detected signal. A simple analysis indicates that the fading rate is proportional to the carrier frequency, f, to the component of wind velocity normal to the propagation path at the height of the scattering volume, and to the angular path distance, θ: providing the path contains no major obstacles θ can, to a first approximation, be taken as proportional to the path length. A more detailed analysis suggests a frequency dependence of the form f^{γ} where γ lies between 1 and $\frac{3}{4}$, the former value being associated with the steady drift velocity of the carriers and the latter with their random motion.

During the period June 1958 to May 1959 about 140 simultaneous measurements of the 9640 Mc/s and 3480 Mc/s median-level fading rates were made at Wembley, a sampling period of 2-3 minutes being used. Cumulative distribution plots of the measurements at the two frequencies are shown in fig. 17. The fading rates have been normalized to their respective median values which at 3480 Mc/s and 9640 Mc/s were 2·4 and 4·8 c/s. The two distributions are quite similar, with

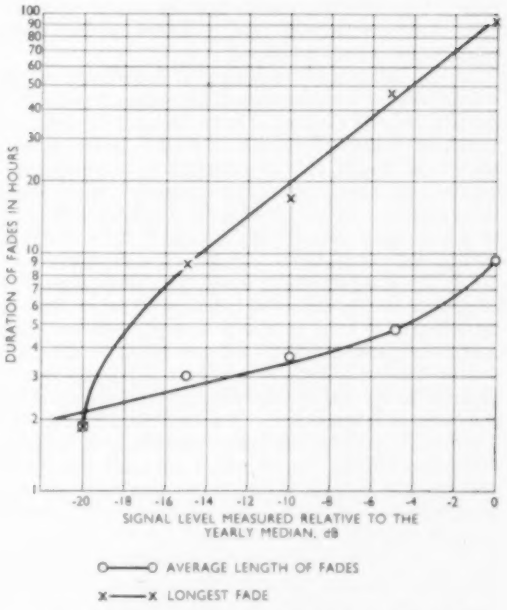


Fig. 19.—Duration of the average fade and longest fade as a function of level.

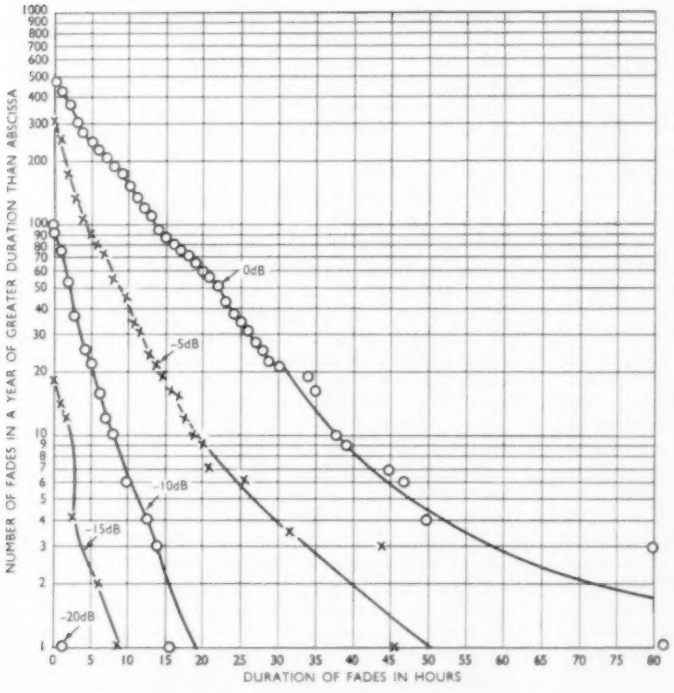


Fig. 18.—Cumulative distribution of the number of fades at various levels, measured relative to the yearly median.

about 90% of the measurements lying in the range 0·4 to 2·0 times the medians. It is interesting to note that the ratio of the median values corresponds to a frequency dependence of $f^{\frac{3}{4}}$. The ratio of the simultaneously determined fading rates at the two frequencies, on the other hand, showed a considerable spread extending beyond the limits of 1·97 and 2·77 corresponding to $\gamma=\frac{3}{4}$ and $\gamma=1$; in fact less than 50% of the results were within the predicted limits. Nevertheless a simple frequency-dependence of the form f^{γ} gives quite a useful guide to the average signal-fluctuation rate.

Investigations of the relation between wind velocity and fading rate have been reported for several links. In general a significant correlation has been found, the correlation coefficient lying typically between 0·4 and 0·7. Less work appears to have been done on the dependence on angular-path distance, but that reported is in approximate agreement with a linear dependence on θ. An additional factor which has so far not been mentioned is the dependence of fading rate on aerial size. The fading rate will decrease with increasing aerial size provided the aerial beam width is less than some critical

value. Experiments indicate that for typical paths this effect will be relatively small provided the half-power beam width is not less than 1°.

In the same way, although a knowledge of the distribution of the hourly medians makes it possible to predict the total number of hours in a year in which the signal drops below a given level it gives no information about the length and distribution of the periods in which these hours occur. An excursion of the short-term median below a given level is usually referred to as a long-term fade to distinguish it from the rapid fading discussed above. In a system designed for a reliability of say 99·9% or more, the distribution of the long-term fading will be of little consequence since the total length of time in a year that propagation effects make the path unusable will not be more than nine hours. However, links of poorer performance may be acceptable for certain applications and in these the distribution is important. In a link with, for example, a reliability of 98% the total outage time in a year is 175 hours (about 7 days) and it is clearly a matter of considerable interest to have some idea how the long-term fades are distributed throughout the year and what their average and maximum lengths are likely to be.

To investigate this problem the results obtained over the 3480 Mc/s link between Start Point and Wembley during 1957 and 1958 were used. Graphs showing the variations in the short-term median were examined at the yearly median and at intervals 5dB below this. The basic data extracted from the curves was the duration of each long-term fade and the interval between successive fades. Cumulative distribution plots of the number of fades and their duration at the various levels are shown in fig. 18. The number of fades have been normalized to apply to a year of continuous operation. It is seen, for example, that there will be 18 fades at 15dB below the yearly median and 14 of these will last for 1 hour or longer. The average duration of fades at the various levels together with the maximum observed values are plotted in fig. 19. Although the total number of fades decreases quite rapidly at levels below the yearly median, the average duration falls away more slowly. For example, at the yearly median and at 15dB below this, the number of fades to be expected in a year are respectively 484 and 18 while the corresponding figures for average duration of fades are 9·1 and 2·8 hours. Futhermore there is likely to be one fade at the 15dB level which lasts up to 10 hours. As might be expected from the seasonal dependence of signal level, the effects of fading are far more serious in the autumn and the winter. A study of the time interval between successive fades showed that they tended to occur, even at low levels, in batches of two or more with relatively small intervals between them. In one period in January 1958, four fades were observed at a level 10dB below the yearly median and these occupied 34 hours out of a total of 56 hours. It can be concluded that for links in which a relatively low reliability is accepted, there may occur continuous periods of two or three days in which the transmissions are very seriously hampered.

BANDWIDTH OF SYSTEM.

Finally the bandwidth properties of a tropospheric system will be briefly discussed. The scattering mechanism is essentially a multipath phenomenon and the component signals travelling by different paths from the transmitter to receiver have different times of transit. This, of course, limits the bandwidth of the signal that can be received without an excessive amount of distortion. The limiting factor is the relative time-delay between the longest and shortest geometric ray paths between the terminals. For relatively low-gain aerials, say less than about 30 dB, the scatter polar diagram of the atmosphere itself will largely determine the extreme paths and the reciprocal of the largest possible time delay in this case is defined as the bandwidth, B, of the scattering mechanism. For paths which include no large obstacles an approximate formula for B is

$$B = \frac{30}{d^3} \text{ Mc/s}$$

where d is the length of the transmission path in units of 100 miles. For $d=1$ the bandwidth is quite large and equal to 30 Mc/s, but for $d=2$ it has reduced to just under 4 Mc/s, barely large enough to accommodate a single television channel. The use of aerials with larger gains and therefore smaller beam widths reduces the size of the effective scattering volume of the atmosphere. The difference between the extreme ray paths is reduced and the bandwidth of the system increased. For example, a 200 mile link using transmitter and receiver aerials with half-power-beam widths of about $\frac{2}{3}°$ has a bandwidth of about 8 Mc/s compared with the 4 Mc/s for the low-gain case. Therefore, although larger aerials have the undesirable property of not realizing their full plane wave gain they do help to increase the bandwidth of a tropospheric scatter system.

CONCLUSION.

The vast amount of experimental work carried out over the last decade has proved beyond any doubt that there is an atmospheric scattering mechanism which makes it possible to transmit signals consistently to large distances beyond the horizon. Although such signals have fluctuating characteristics, the nature of these is fairly well understood and diversity techniques are available to minimize their effect. At the present stage, the most undesirable feature from the point of view of engineering a system is the inability of the theory to predict the long-term median signal level to the desired degree of accuracy. Nevertheless the experiments have demonstrated the feasibility of this method of long-distance communication and many systems are already in operation. In general, the equipment required is more costly than for the conventional line-of-sight system with repeater stations, and scatter systems would only appear to be economic for mountainous or oversea paths where the installation of repeaters is impractical. However, it seems certain that in the future development of long-distance communications many requirements will arise for which the tropospheric scatter system provides the best solution.

TECHNICAL LITERATURE

A digest of recent articles and papers by members of the G.E.C. and its associated companies

INFRA-RED FARADAY ROTATION IN InAs AND InP (929).*

By I. G. Austin (Hirst Research Centre).

Journal of Electronics and Control **8**, 3, *p.* 167, *March* 1960.

The use of Faraday rotation in semiconductors to determine the effective mass of charge carriers has been demonstrated recently for InSb (Smith *et al.* 1959), Ge (Walton and Moss 1959), GaAs and InP (Moss and Walton 1959 a, b) and Bi_2Te_3 (Austin 1959).

Similar measurements have now been made at room temperature for InAs and InP covering the range 2-17 μ. The method differs somewhat from that used by other workers. Transmission through the crystal in a direction parallel to the magnetic field was obtained by means of two small mirrors situated between the magnet pole-pieces and angled at 45° to the main beam direction. The results indicate that rotations up to ~60° could be measured without serious errors arising from the depolarizing effects at the mirrors.

THE ASYMPTOTIC EFFICIENCY OF DANIELS'S GENERALIZED CORRELATION COEFFICIENTS (935).*

By D. J. G. Farlie (Hirst Research Centre).

Journal of the Royal Statistical Society (*Series B*), **23**, 1, 1961.

The asymptotic efficiency of the generalized correlation coefficient devised by Daniels, used as a test of association in the bivariate function $H(x,y) = F(x)G(y)\{1 + \alpha A(x)\ B(y)\}$, is shown to depend in a simple way on the score-matrices used to define the coefficient. Two coefficients for which the corresponding row sums of the two score-matrices, written in a standard form, are proportional are shown to have the same asymptotic efficiency. In particular, this is shown to be true for Spearman's rank correlation coefficient and Kendall's alternative coefficient, τ. For alternatives of the above type, maximum efficiency can be obtained within Daniels's family of coefficients; for a more general class of alternatives a weighted combination of Daniels's coefficients is necessary to attain maximum asymptotic efficiency.

GENERAL STEADY-STATE THEORY OF LINEAR MAGNETRONS. I (938).*

By P. A. Lindsay (Hirst Research Centre).

Journal of Electronics and Control, **8**, 3, *p.* 177, *March* 1960.

This paper presents a general steady-state theory of linear magnetrons. Space charge and the Maxwellian velocity distribution of the emitted electrons are taken into account, but the collisions between individual electrons are neglected. Part I of the paper explains the mathematical basis of the calculations and gives expressions for the volume density of the electrons and for the two components of the electron current density. A detailed analysis of these expressions is provided in Part II of the paper. No calculations of the actual potential distribution are given.

SOME PROBLEMS IN THE POWDER METALLURGY OF TITANIUM (961).*

By S. E. Rogers (Hirst Research Centre).

Powder Metallurgy No. 7, 1961.

An investigation is described of problems encountered in the conventional powder metallurgy of titanium, with particular reference to the pressing and sintering characteristics of titanium and titanium hydride powders and to sources of contamination. It is concluded that, for success to be achieved in the production of fully dense sintered material by the present method without incurring serious contamination, commercial titanium would have to be available as powder conforming to strict purity requirements.

THE RAPID DETERMINATION OF ALUMINA IN OPAL GLASS (965).*

By H. J. Cluley (Hirst Research Centre).

Glass Technology **2**, 2, *April* 1961.

To facilitate analytical control of glass composition, a rapid method of determining alumina in opal glass has been devised.

After decomposition of the glass sample with hydrofluoric and perchloric acids, aluminium, zinc, etc., are complexed with ethylenediaminetetra-acetic acid (EDTA) and the excess of this reagent is removed by titration with zinc solution. Sodium fluoride is then added to displace EDTA from its complex with aluminium and the determination is completed by titration of the liberated EDTA with standard zinc solution. The method is capable of high precision; results on a sample of opal glass containing 4% of alumina had a standard deviation of 0·01% Al_2O_3. After a crushed sample of glass has been prepared duplicate determinations can be completed in 1½ to 2 hours.

THE RAPID DETERMINATION OF FLUORINE IN OPAL GLASS BY PYROHYDROLYSIS (966).*

By H. J. Cluley (Hirst Research Centre).

Glass Technology **2**, 2, *April* 1961.

To facilitate analytical control of glass composition, a rapid method for determining fluorine in opal glass has been devised, using the technique of 'pyrohydrolysis'.

The ground glass sample, together with uranium oxide as an 'accelerator', is maintained at 1050° C in a current of steam and the fluorine in the glass is liberated as hydrogen fluoride. The emergent steam is condensed and the fluorine in the condensate is determined by titration with thorium nitrate solution. The method is capable of high precision; results on a sample of opal glass containing 5% of fluorine had a standard deviation of 0·02% F. After a crushed sample of glass has been prepared the determination can be completed in 1 hour.

TITANIUM—ALUMINIUM—MANGANESE ALLOYS PREPARED BY POWDER/METALLURGICAL TECHNIQUES (968).*

By M. F. Grimwade (Hirst Research Centre).

Powder Metallurgy, 1961, *No.* 7.

The preparation of titanium hydride powder and the method of adding aluminium and manganese are described. Sintered materials had poor ductility and this is attributed to the presence of an acicular structure. The tensile strength and ductility of sintered and forged alloys, in which the acicular structure is destroyed, were as good as, and in some cases superior to, those of the equivalent conventional cast and wrought alloy. Both the sintered and the sintered and forged material exhibited good creep properties at 200 and 400° C. Attempts to destroy the acicular structure of the sintered alloy by heat-treatment were unsuccessful.

BODE'S VARIABLE EQUALIZER—DESIGN CRITERIA.*

By S. S. Hakim (Telecommunications Group, Coventry).

Electronic Technology **38,** 6, *pp.* 224-227, *June* 1961.

The need often arises for the design of an equalizer in which the insertion-loss characteristic can be varied to compensate, for example, for the variation of the loss of a cable with temperature. Bode has described several types of variable equalizers in which the insertion-loss characteristic can be varied by the variation of the value of one of its elements, e.g. a thermistor. This article develops the basic theory for one particular type of Bode's variable equalizer, and concludes with a typical design example.

RADIO WAVE PROPAGATION AND ATTENUATION IN THE TROPOSPHERE.

By E. M. Hickin (Hirst Research Centre).

Research **13,** *pp.* 503-506, *December* 1960.

As the possible application of radio waves are further investigated the pressure on spectrum space becomes very great. Higher and higher frequencies are now coming into use and the estimation of the magnitude of microwave loss due to meteorological phenomena is important in further exploitation of the spectrum.

VISION AND EYE MOVEMENTS OF MOTOR DRIVERS.

By J. M. Waldram (Hirst Research Centre).

The New Scientist **8,** 10, *November* 1960.

In experiments described here, eye movements of observers were recorded while they were viewing a film of streets taken from a vehicle at night, simulating driving conditions. Conclusions are drawn concerning the processes of vision while driving. Further tests are contemplated.

PROGRESS IN ELECTRIC LAMPS.

By H. G. Jenkins (Hirst Research Centre).

Transactions of the Illuminating Engineering Society **26,** 1, *pp.* 17-32, 1961.

During the past twenty-five years there has been spectacular progress in the development of electric lamps. While this applies mainly to discharge sources, much work has gone into incandescent lamps, which, despite their relatively low luminous efficiency, have not diminished in importance. An entirely new method of converting electrical energy into light by electroluminescence has been evolved, which, however, has not fulfilled its early promise. On the other hand, at a time when progress in conventional discharge sources might reasonably be expected to have levelled off, new ideas have evolved and substantial improvements have been made. The paper discusses the more important developments and trends in the field of electric lamps.

A NOTE ON CALCULATIONS OF DISABILITY GLARE, VEILING AND CONTRAST.

By J. M. Waldram (Hirst Research Centre).

The Transactions of the Illuminating Engineering Society **25,** *pp.* 131-134, 3, 1960.

The effects of disability glare and veiling are shown in a new method of plotting object and background luminance, suited to their graphical calculation. The conspicuousness of objects not near the threshold can be estimated by the differences in apparent brightness which they present under the conditions considered.

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